NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

INCORPORATING MULTI-CRITERIA OPTIMIZATION AND UNCERTAINTY ANALYSIS IN THE MODEL-BASED SYSTEMS ENGINEERING OF AN AUTONOMOUS SURFACE CRAFT
by
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September 2009
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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2009	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Incorporating Multi-criteria Optimization and Uncertainty Analysis in the Model-Based Systems Engineering of an Autonomous Surface Craft			**5. FUNDING NUMBERS**
6. AUTHOR(S) Jon P. Letourneau			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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This thesis uses model-based systems engineering (MBSE) principles to develop a multi-criteria decision making (MCDM) model that allows designers to perform a solution neutral investigation of possible alternative physical architecture concepts. This ensures a consistent quantitative evaluation of warfighting capability, suitability, effectiveness, technology maturation, and risk before and during a program execution. This effort is in support of an extended program to design a system of unmanned systems intended to provide the DoD with a coordinated, multi-domain, multi-mission, autonomous security and warfighting asset.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
Autonomous, Unmanned vehicle, USV, UV Sentry, Model-Based, Multi-criteria, Model-Based Decision Making, MCDM, Unmanned Surface Vessel, Model-Based Systems Engineering, MBSE, Uncertainty			117
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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INCORPORATING MULTI-CRITERIA OPTIMIZATION AND UNCERTAINTY ANALYSIS IN THE MODEL-BASED SYSTEMS ENGINEERING OF AN AUTONOMOUS SURFACE CRAFT

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING
AND
MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

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LIST OF ABBREVIATIONS AND ACRONYMS

AIS	Automated Identification System
AOR	Area of Responsibility
ASN	Assistant Secretary of the Navy
ASW	Anti-Submarine Warfare
ATR	Automated Target Recognition
AV	All View
CADM	Core Architecture Data Model
CBA	Capabilities-Based Assessment
CBP	Capabilities-Based Planning
CBRN	Chemical, Biological, Radiological, Nuclear
CCD	Combat Craft Division
CDF	Cumulative Distribution Function
CIEL	Common Information Element List
COAL	Common Operational Activities List
COCOM	Combatant Commander
COI	Contacts of Interest
CONL	Common Operational Node List
CONOPS	Concept of Operations
COP	Common Operational Picture
COTS	Commercial Off the Shelf
CSFL	Common Systems Function List
CSL	Common Systems List
CSNL	Common System Node List
DNC	Digital Nautical Chart
DoDAF	Department of Defense Architecture Framework
DOE	Design of Experiments
DRM	Design Reference Mission
ERA	Element Relationship Attribute

EW	Electronic Warfare
GPS	Global Positioning System
GWOT	Global War on Terror
HM&E	Hull, Mechanical and Electrical
HVA	High Value Asset
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineering
IFF	Identification Friend or Foe
ISR	Intelligence, Surveillance, Reconnaissance
JCIDS	Joint Capabilities Development System
JMET	Joint Mission Essential Tasks
JMETL	Joint Mission Essential Task List
JMP	Jump
LCG	Longitudinal Center of Gravity
LOS	Line-of-Site
LSL	Lower Specification Limit
MBD	Model-Based Design
MBSE	Model-Based Systems Engineering
MCDM	Multi-Criteria Decision Making
MCM	Mine Countermeasure
MCTL	Marine Corps Task List
MIO	Maritime Interdiction Operations
MIW	Mine Warfare
MLA	Manitobi Liberation Army (fictional)
MOE	Measures of Effectiveness
MOP	Measures of Performance
MS	Maritime Security
NAERG	Naval Architecture Elements Reference Guide
NM	Nautical Miles
NMET	Naval Mission Essential Task

NMETL	Naval Mission Essential Task List
NSWC	Naval Surface Warfare Center
NTA	Naval Tactical Task
NTTL	Navy Tactical Task List
ONR	Office of Naval Research
OPSITS	Operational Situations
OTH	Over-the-Horizon
OV	Operational View
PEO LMW	Program Executive Officer for Littoral and Mine Warfare
POE	Projected Operational Environment
PSV	Platform Supply Vessel
R&D	Research and Development
RDA	Research, Development, and Acquisition
RIB	Rigid (hull) Inflatable Boat
ROE	Rules of Engagement
RPG	Rocket Propelled Grenade
RSM	Response Surface Methods
SAS	Statistical Analysis Software
SE	Systems Engineering
SEP	Systems Engineering Process
SHP	Shaft Horsepower
SIGINT	Signals Intelligence
SME	Subject Matter Experts
SOF	Special Operations Forces
SoS	System of Systems
SUW	Surface Warfare
SV	Services View
SWATH	Small Waterplane Area Twin Hull
TTCP	The Technical Cooperation Program
TV	Technical Standards View

UAS	Unmanned Aircraft Systems
UGV	Unmanned Ground Vehicles
UJTL	Universal Joint Task List
UMS	Unmanned Maritime System
UNTL	Universal Naval Task List
USCG	United States Coast Guard
USL	Upper Specification Limit
USV	Unmanned Surface Vessel
UUV	Unmanned Undersea Vehicle
UV	Unmanned Vehicle
UxV	Unmanned (air, surface, undersea, ground, or combination) vehicle
V&V	Verification and Validation

EXECUTIVE SUMMARY

Like all engineering projects, this thesis began with a question: How do Department of Defense (DoD) engineers efficiently and effectively design an autonomous surface vessel in support of an overarching Office of Naval Research (ONR) Unmanned Vehicle (UV) system of systems (SoS)?

Traditional DoD engineering practices include a threat-based or technology-driven design process, focusing on the system components the designers feel will effectively counter an adversary's current and future capabilities. This bottom-up approach to system design typically misses the mark in meeting stakeholder capability needs and fails to effectively perform the intended mission. The process typically results in the designer following predetermined design concepts leading to an unfavorable solution. In addition, the approach almost always results in allocating large amounts of money and assets in areas that are well outside the feasible design region of the project, wasting valuable resources better spent elsewhere.

This thesis offers an alternative approach to this engineering problem based on a capabilities-driven, model-based, SoS engineering process. This holistic approach to system design keeps the design concepts and the designer in the feasible region with respect to physical, systematic, and capability constraints. It presents an effective methodology and tool set to enable design, development, and assessment of alternative system concept architectures for an autonomous unmanned surface vessel (USV) in a SoS context.

Using model-based systems engineering (MBSE) principles and a derived multi-criteria decision making (MCDM) model allow designers to perform a solution neutral investigation of possible alternative physical architecture concepts. This ensures a consistent quantitative evaluation of warfighting capability, suitability, effectiveness, technology maturation, and risk before and during a program execution. This effort is in

support of an extended program to design a system of unmanned systems intended to provide the DoD with a coordinated, multi-domain, multi-mission, autonomous security and warfighting asset.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my “sweet Melissa” for her love, support, and patience during my late nights and busy weekends at Naval Postgraduate School. You mean the world to me and deserve these degrees just as much as I do.

I want to thank my family for being loving and understanding during my secluded years on the “Left Coast.”

I would also like to thank Dr. Cliff Whitcomb and Dr. Fotis Papoulias for their guidance and mentoring throughout my pursuit of a dual degree and during the thesis research and writing processes.

Lastly, thanks to Dave and Lawrence for helping wrap up the loose ends in those last few late nights in Bullard Hall. The next two rounds are on me.

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I. INTRODUCTION

A. OVERVIEW

This thesis presents an effective methodology and tool set to enable design, development, and assessment of alternative system concept architectures for an autonomous unmanned surface vessel (USV) in a SoS context. The methodology provides a consistent quantitative evaluation of warfighting capability suitability, effectiveness, technology maturation, and risk before and during a program execution. This effort is in support of an extended program to design a system of unmanned systems intended to provide the DoD with a coordinated, multi-domain, multi-mission autonomous security and warfighting asset.

The methodology is capabilities-driven, based on thorough generation and review of mission-based ability to deliver a set of desired effects. The MBSE method allows for solution neutral investigation of possible alternative physical architecture concepts to meet overall SoS needs based on a traceable path to the capabilities desired as documented by the stakeholders. The method developed provides the best way to compare alternative architectures and assess technological maturity of critical subsystems in meeting stakeholder capability needs.

The architecture structure is created, defined, edited, and configuration controlled and managed using Vitech CORE. Linkages to engineering feasibility analysis are accomplished using Microsoft Excel, though other domain specific science, engineering, and analysis software tools could also be used. Design space creation, exploration, and trade-off is accomplished using Microsoft Excel and Statistical Analysis Software (SAS) Institute JMP. Technology assessments and associated uncertainty analyses are accomplished using SAS Institute JMP.

Unmanned vehicle (UxV) systems are particularly susceptible to missing the mark in meeting stakeholder needs, especially due to advanced concepts, inclusion of uncertain technology, the need to fuse diverse elements, multifaceted integration issues, and the manifestation of emergent properties. SoS are described as (Boardman and Sauser 2008)

> . . . a large-scale, complex system, involving a combination of components which are systems themselves, achieving a unique end-state by providing synergistic capability from its component systems, and exhibiting a majority of the following characteristics: operational and managerial independence, geographic distribution, emergent behavior, evolutionary development, self-organization, and adaptation.

Designing a SoS requires an architecture development method that implements executable architectures that can be used to model and simulate behaviors during the design process.

System architecture development is based on systems engineering principles and involves expanding the areas of identifying a capability gap or need, defining and refining architectural and engineering system requirements, analyzing system functions, allocating system functions to physical components, and the application of executable models. Building the UV Sentry system of systems architecture requires a thorough MBSE method to ensure success in meeting stakeholder capability needs and transforming them into an effective SoS design.

The first three chapters of this thesis build a solid knowledge base of the concepts and techniques behind this innovative method. Chapter I provides a necessary overview of the engineering and architecture development terms, processes, and concepts involved with the design approach. Chapter II provides a description of the UV Sentry system as a whole and the unmanned surface vehicles aspects of the system of systems. Chapter III describes the elements and techniques used in building the system architecture and model-based design tools. The final two chapters describe how to build and use the MCDM model. Chapter IV presents the architecture development and analysis method for the UV Sentry unmanned surface vessel using the tools and techniques described in the first three chapters. Chapter V provides a summary, conclusions, and recommendations for follow-on work.

This thesis provides UV sentry designers with the appropriate tools and processes to effectively focus their research and acquisition efforts. This focus will prevent the

unnecessary disbursement of resources into non-critical or unfeasible areas. This will permit system designers to focus efforts in areas where they are needed and will have a positive effect on the overall design.

B. BACKGROUND

Unmanned systems have increasingly become an integral element of a wide range of modern military operations over the past decade. Unmanned systems performed vital roles on the ground, in the water, and in the skies during military operations in Iraq and Afghanistan. The DoD anticipates these systems will play an even larger role in future military operations. The Secretary of Defense's Unmanned Systems Integrated Roadmap FY 2009-2034 highlights this with:

> In today's military, unmanned systems are highly desired by combatant commanders (COCOMs) for their versatility and persistence. By performing tasks such as surveillance; signals intelligence (SIGINT); precision target designation; mine detection; and chemical, biological, radiological, nuclear (CBRN) reconnaissance, unmanned systems have made key contributions to the Global War on Terror (GWOT). As of October 2008, coalition unmanned aircraft systems (UAS) (exclusive of hand-launched systems) have flown almost 500,000 flight hours in support of Operations Enduring Freedom and Iraqi Freedom, unmanned ground vehicles (UGVs) have conducted over 30,000 missions, detecting and/or neutralizing over 15,000 improvised explosive devices (IEDs), and unmanned maritime systems (UMSs) have provided security to ports."
>
> The report continues: "In response to the Warfighter demand, the Department has continued to invest aggressively in developing unmanned systems and technologies. That investment has seen unmanned systems transformed from being primarily remote operated, single-mission platforms into increasingly autonomous, multi-mission systems (OSD 2009).

The vulnerability of personnel and high value assets coupled with the high cost of manned platforms fuels the drive for the UV Sentry SoS. The asymmetric nature of the threats and the vast coverage areas intensify the need to have a coordinated network of unmanned vessels to accomplish the dirty, dull, and dangerous tasks that are now performed with manned assets. The UV Sentry vision involves a versatile fusion of unmanned surface, subsurface, and airborne vehicles, hereafter generically referred to as

(UxV), accomplishing a broad set of capabilities providing persistent effective defense of naval and maritime assets using manned and unmanned systems. The system will provide information, surveillance, and reconnaissance (ISR) to improve situational awareness around a high-value asset (or group of assets). This SoS will take action at sufficient distances to neutralize or deter detected threats, autonomously operating and sharing information between system elements.

The DoD vision of future operations calls for vastly improved autonomous vehicles and greater synergy between air, ground, and maritime assets. The multitude of missions, domains, and environments coupled with the asymmetrical nature of the threats adds an unprecedented level of complexity facilitating the need for a SoS engineering approach to the problem. The current scope of the majority of unmanned vehicle programs is bound within a limited mission in a single domain. The UV Sentry initiative seeks to expand this scope to cover a multitude of security related missions in three domains (air, surface, and sub-surface). Although the technology maturation for a fully coordinated, multi-domain, multi-mission, fleet of autonomous vehicles is a work in progress, a clear and coordinated plan is required to develop a future unmanned system of systems. The UV Sentry program is committed to providing a coordinated effort in transforming disjointed, stand-alone, unmanned vehicle initiatives into a collaborative design and acquisition approach. This approach is intended to set a solid foundation for future UV research, development, and acquisition. Without this integrated approach to force application and mission accomplishment, the project will most likely lead to an ineffective and disordered design.

C. OBJECTIVES

The overall objective of this thesis is to set the foundation for the development of a system of systems architecture development and engineering design process that for the development of the future U.S. DoD UV Sentry SoS.

This Thesis:

- Provides a synopsis of the fundamental design concepts used.
- Explains the scope and methodology of the project.
- Provides an overview of unmanned systems, the UV Sentry initiative, and autonomous surface craft missions, classifications, and design concerns.
- Provides an overview of the design tools and techniques used in this project.
- Describes how to build the model.
- Describes a real-world example of the process using actual ship synthesis information.
- Briefly covers how statistical methods can be used to study the impact of stochastic inputs and uncertainty in conceptual design.
- Provides a summary, conclusions, and recommendations based on this study's findings.

D. CONTEXT

The UV Sentry program is implementing the development process shown in Figure 1. This section provides a synopsis of the fundamental design concepts used in this process, and applied to a specific methodology is used to accomplish a MBSE trade study analysis for the UV Sentry program.

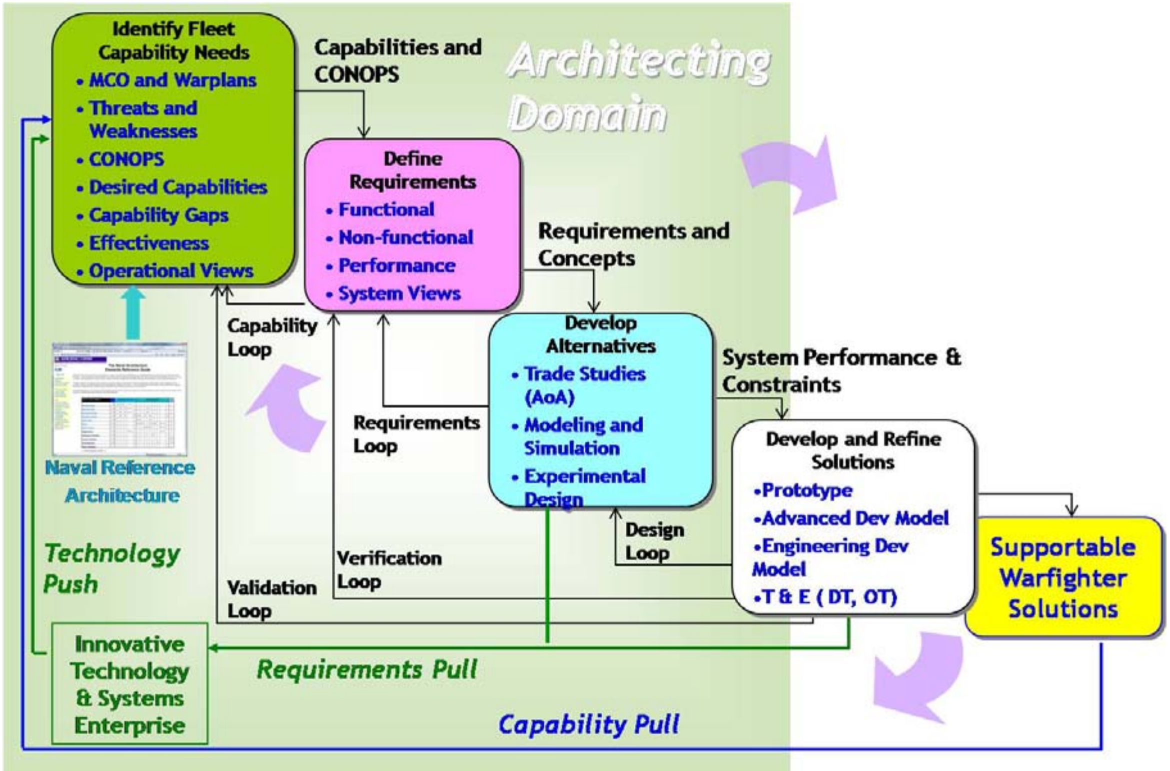

Figure 1. UV Sentry Architecture Synthesis. (From: Whitcomb et al. 2008)

1. Capabilities-Based Planning (CBP)

CBP is a systematic force development approach that aims to develop the most appropriate options to meet priorities such as strategic objectives, cost and risk minimization, and constraint compliance (TTCP 2007). This method involves a functional analysis of operationally required capabilities based on the tasks required to perform the respective mission(s). Once the capabilities are defined, the most cost effective and efficient options that satisfy the requirements are sought (TTCP 2007). Figure 1 shows the capabilities-based development method embedded in the SE process. The Capability Pull loop ensures capability needs are iteratively reviewed, analyzed, and revised throughout the SE process.

This development process marks a transformation in DoD's approach to system requirements definition and defense planning from a from a "threat-based" to a "capabilities-based" model. This process focuses on identifying the capabilities required to solve a problem and delivering those capabilities to the system. CBP attempts to

eradicate traditional stovepipes, making the planning process more lucid, rational, and responsive to uncertainty, economic constraints, and risk. The CBP process focuses on overarching goals and end-states supporting analysis, facilitating risk management, and encouraging innovation. CBP forces system designers to ask *what do we need to do* rather than *what equipment are we replacing* (TTCP 2007). CBP uses scenarios to provide the context within which the system will operate. This context is then used to determine what capabilities are required for the system to meet its stated needs and how to measure its level of capacity. Capabilities, often referred to as operational scenarios, consist of a sequence of operational activities needed to respond to or to provide an external stimulus (Whitcomb et al. 2008). Anticipated operational scenarios are developed in support of a higher-order concept of operations (CONOPS) that describes the anticipated strategic, operational, and tactical levels of system employment. Valid and well-defined CONOPS are essential inputs to a successful capabilities-based planning/design process. The CONOPS, and associated operational scenarios, drive the conceptual design process and provides a means for developing goals against which capabilities are assessed (TTCP 2007).

The capabilities-based approach is realized in the DoD through the Joint Capabilities Integration Development System (JCIDS). JCIDS is the DoD’s principal decision-making process for transforming the military in support of future strategic goals. JCIDS uses a collaborative process, utilizing joint concepts and integrated architectures, to identify capability gaps and approaches to bridge them (CJCS 2009). A capability need is a required function that a system must possess within specified conditions and to essential performance levels. A capability gap is the inability to achieve a desired effect under specified conditions and standards through combinations of resources and techniques to perform a set of tasks (CJCS 2009). A Capabilities-Based Assessment (CBA) is conducted, in accordance with JCIDS, to identify capability needs, gaps, excesses, and approaches to provide needed capabilities within a specified functional or operational area (CJCS 2009). Once the CBA is complete and the required capabilities are identified, the JCIDS process works to transform capabilities into solutions.

Implementation of this capability-based development process is the front-end to the system acquisition and development process, which must keep the process focused on the problem space versus the solution space (Whitcomb et al. 2008). The outcome is the system architecture, which defines system functions, elements, and relationships. The architecture is the embodiment of the system and should be understood and agreed upon by all stakeholders and validated to meet all established capability needs.

2. Systems Engineering Process (SEP)

The DoD defines systems engineering as:

> Systems engineering is an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and total life cycle balanced set of system, people, and process solutions that satisfy customer needs. Systems engineering is the integrating mechanism across the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for systems and their life cycle processes. Systems engineering develops technical information to support the program management decision-making process (OSD 2002).

Systems engineering is typically described as having two domains: the technical knowledge domain in which the systems engineer operates; and the systems engineering management domain where the project management occurs (OSD 2002).

The Systems Engineering Process (SEP), displayed in Figure 2, is a comprehensive, iterative and recursive problem solving process, for transforming needs and requirements into a set of system product and process descriptions. The process is applied sequentially, one level at a time, adding additional detail and definition with each level of development (OSD 2002). This process typically begins by identifying the problem and associated stakeholders. The problem is then properly defined and refined to ensure it properly describes the customer’s need(s). Process inputs include customer needs/requirements, technology base, and other requirements the system must meet.

The first step of the process is the Requirements Analysis phase. Here system missions and environments are analyzed, functional requirements identified, and design constraints defined. This step develops a comprehensive and logical set of performance

requirements that detail what, where, and how well the system must perform. This step is particularly important as an ill-defined set of requirements will typically not be met.

The next part of the SE process is the functional analysis phase. Here functions are decomposed, requirements are linked to various level functions, interfaces are defined, and the functional architecture is defined and refined. The functional architecture is the description of the product in terms of what it does. This architecture is illustrated with a functional hierarchy diagram that displays the structure of higher-level functions and their respective derivation to lower-level functions. This hierarchy provides decision makers with a clear vision of actual system functions and how the functions are associated with one another.

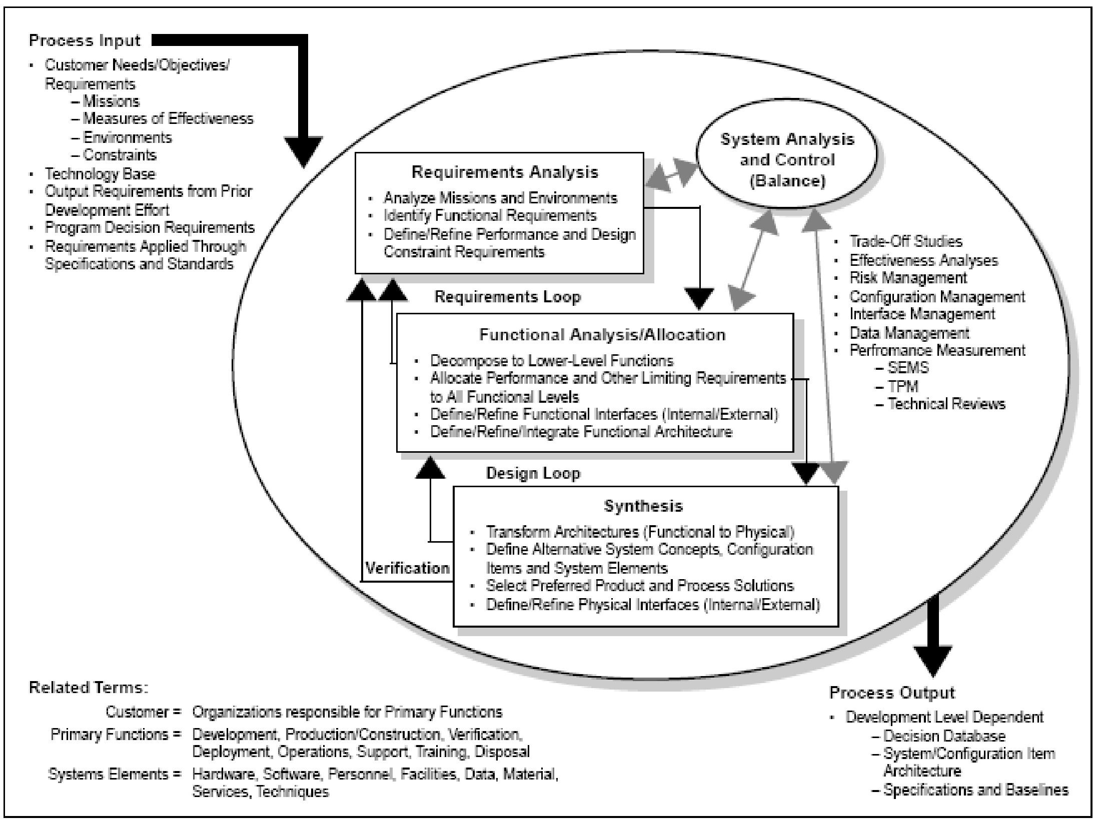

Figure 2. Systems Engineering Process. (From: DAU 2001)

The final process stage is the synthesis phase. Here the functional architecture is mapped to the physical architecture; alternative system concepts, configuration items, and

system elements are defined; preferred process and product solutions are selected; and internal and external physical interfaces are defined. In general, design synthesis is the process of defining the physical architecture of the system in terms of its physical elements with each physical element meeting at least one functional requirement. “The physical architecture is the basic structure for generating the specifications and baselines” (OSD 2002). This phase may also involve the use of development tools such as: trade-off studies; risk analysis and management; and interface management.

Each phase of the process is not complete after its first incidence. The processes include recursive loops for an iterative development process. The Requirements loop provides feedback from the Functional Analysis section to the Requirements Analysis section. This provides the means of mapping requirements to functions and back to make certain all functions are linked to a requirement. Any function not linked to a requirement is wasted effort; any requirement not linked to a function will never be met. The Design loop links the Synthesis and Functional Analysis phases providing a cyclic process for mapping functional architecture to physical architecture. This process maintains continuity in the systems architecture model, ensuring all functions have physical elements to perform them. “The design loop permits reconsideration of how the system will perform its mission, and this helps optimize the synthesized design” (OSD 2002). In addition to the Design loop, the Synthesis phase involves a Verification feedback element to ensure all the requirements are met by the physical architecture. The verification process is a formal testing and evaluation method to ensure the proposed solution meets all of the requirements.

The Systems Analysis and Control process provides the control mechanism for the iterative SE process. This process step provides general developmental oversight and coordination as alternative system approaches are analyzed in each phase of the systems engineering process. This oversight is essential in balancing all aspects of the SE process including trade-off studies and risk management. In addition, the process assures alternative system decisions are made only after their system effectiveness impact is evaluated and that product and process design requirements are directly traceable to functional and performance requirements (OSD 2002). The primary output of the SE

process is the system architecture. The system architecture includes the physical and functional hierarchies and the system specifications. The systems engineering process output provides the necessary information to illuminate the conceptual system design and describes system characteristics such as cost, performance, and risk.

3. System of Systems Engineering

SoS describes an integrated arrangement of interoperable systems acting as a single functional entity to achieve a mission capability. A SoS is defined by Boardman and Suaser (2008) as:

> …a large-scale, complex system, involving a combination of components which are systems themselves, achieving a unique end-state by providing synergistic capability from its component systems, and exhibiting a majority of the following characteristics: operational and managerial independence, geographic distribution, emergent behavior, evolutionary development, self-organization, and adaptation (Boardman and Sauser 2008).

Typical characteristics of a system of systems include a high degree of collaboration and coordination, flexible addition or removal of component systems, and a net-centric architecture (ASN RDA 2006). The SoS possesses capabilities not possessed by the simple sum of the constituent capabilities operating separately. Individual SoS elements are typically able to operate independently and may be separately managed. Management, organization, integration, and interoperability between the constituent systems are often major challenges for SoS development and implementation.

A system of systems is often confused with a family of systems. In a system of systems, subsystems are related or connected to provide a given capability. The loss of any part of the system will degrade the performance or capabilities of the whole. In a family of systems, subsystems provide similar capabilities through different approaches to achieve similar or complementary effects (CJCS 2009). Five principal characteristics that distinguish systems of systems from monolithic systems are: a SoS is composed of systems which are independent and useful in their own right; managerial independence of the systems; large geographic distribution; evolutionary development; and emergent behavior (Sage 1992).

SoS engineering is an emerging interdisciplinary approach to transform capabilities into SoS solutions. The architecture development of an SoS starts with the transformation of an operational capability need into a set of requirements, which are used to guide the development of functional and physical architectures through design (Whitcomb et al. 2008).

4. System Architecture

Systems Architecture is "the fundamental organization of a system, embodied in its components, their relationships to each other, and to the environment, and the principles governing its design and evolution" (IEEE 2000). Systems Architecting is the process used to develop and revise the system architecture. Systems architecture development, like the SEP, is an iterative process involving participative discovery of multiple stakeholders to achieve an end state. In systems architecture development, however, the end state is a well-defined, clear, all-inclusive, agreed-upon, systems architecture that meets all capability requirements. Systems architects must work to reduce ambiguity, minimize complexity, and focus creativity, to transform the capability need from the abstract to the concrete through a series of ever-evolving models of continually improved fidelity (Southworth 2008).

Systems architecture development and systems engineering are both essential components of the overall systems engineering process, both presenting complementary approaches to the development of unprecedented (or as-yet fully conceived) SoS (Whitcomb et al. 2008). Architecting focuses on the qualitative aspects of the system and typically deals with undefined situations with immeasurable quantities. Engineering primarily deals with physical and scientific situations with measurable quantities and concepts (Maier and Rechtin 2002). DoD architecture development is directed by the JCIDS process and should start early in the systems engineering process and be introduced in the earliest part of the acquisition process. System designers must pay particular attention not to fall into the trap of trying to describe the total system to the individual component level before bounding the requirements and properly developing the system architecture. This mistake has the system designer focusing on components

rather than capabilities, resulting in an ill-formed architecture. The systems architecture development approach focuses on architecture development from capability needs. The ultimate goal of systems architecture development is to provide a well-defined system in the application domain and system that meets desired capabilities developed in the solution domain (Southworth 2008).

The relationship of the system and the architecture are shown in Figure 3 (IEEE 2000). A system fulfills a mission and inhabits and influences an environment. A system also has stakeholders, who have concerns that must be met through the use of the system. A system has an architecture, which is described by a description that provides rationale, which is used by the stakeholders to ensure their concerns are addressed. The description consists of views that conform to the stakeholder’s viewpoint. A model is used to represent the system structure, and allow for reasoning about that structure. Multiple architectural “views” are needed to allow stakeholders to communicate with the architects and other stakeholders in their own language to ensure their concerns are addressed. All views are derived from a single system structure, the architecture model, with each view acting as a lens projecting an image in the stakeholder’s own native language as defined by their own viewpoint. Architecture, then, exists for the purpose of achieving a well-defined system in all domains, such that the eventual system developed will meet operator’s desired effectiveness An architecture model is the fundamental basis for engineering a system since it is the foundation upon which the entire development depends (Whitcomb et al. 2008).

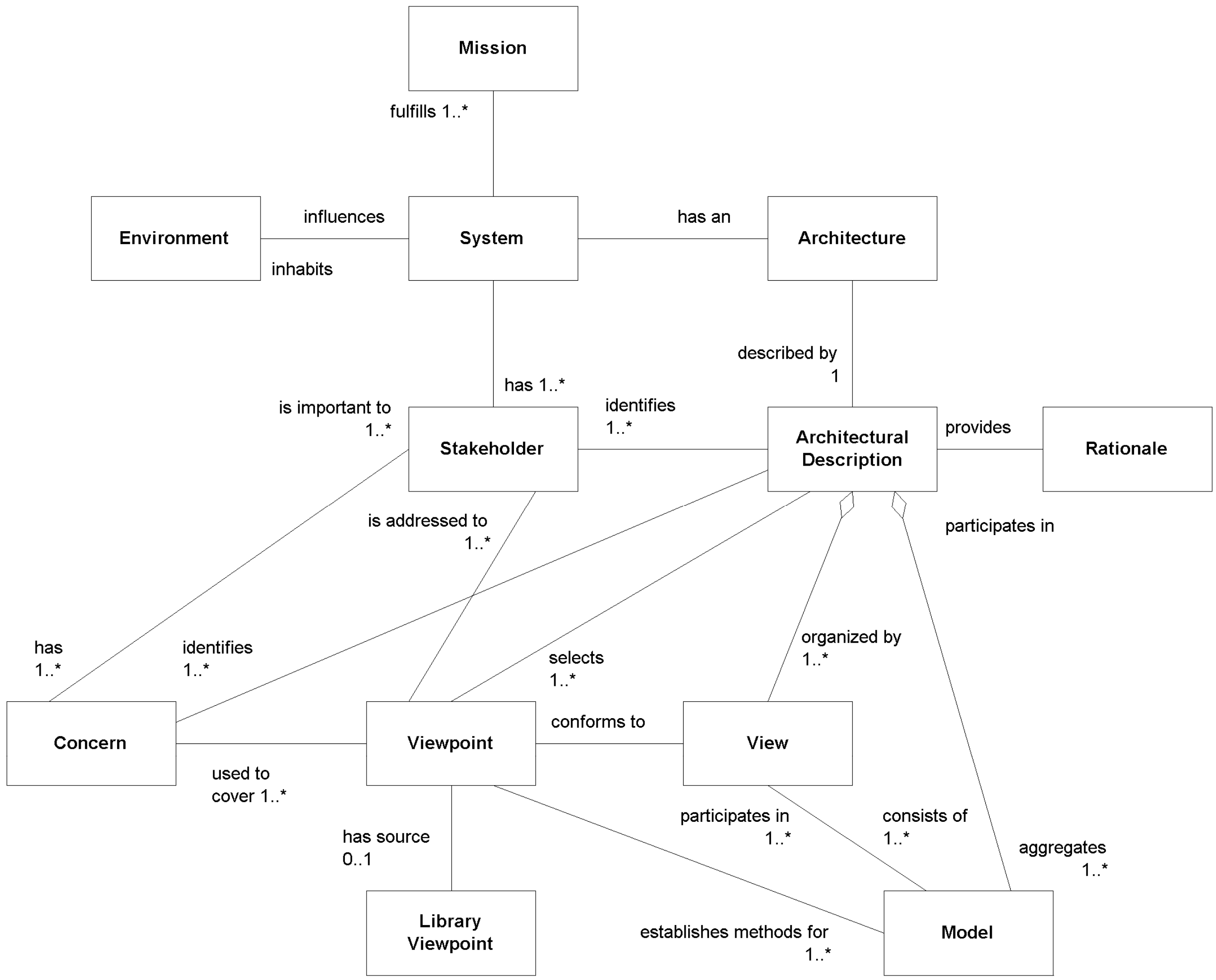

Figure 3. IEEE 1471 Conceptual Framework. (From: IEEE 2000)

Complex systems present enormous amounts of elements and interconnections in the architecture model. This sheer amount of data, coupled with the need to manipulate, change, and display architecture information, facilitates the need for a better means to communicate and influence architectural relationships. Architecture frameworks are tools for coping with system complexity by structuring data into different views with common communication language providing consistency and traceability to system characteristics descriptions. The architecture is defined through a series of views, each depicting the architecture in a perspective that addresses a respective stakeholder's needs (Whitcomb et al. 2008). "A view is a projection of the enterprise architecture model that is meaningful to one or more system stakeholders" (DoD 2007). Architecture frameworks aid decision

makers in making design choices by providing clear, comprehensive, functional system descriptions understood by all of the system stakeholders. The United States military uses the DoD Architecture Framework (DoDAF) as its standard systems architecture framework. The DoDAF classifies and organizes the development of complex systems to aid in successful system design and implementation.

a. DoD Architecture Framework (DoDAF)

The DoDAF defines how to organize enterprise architectures for U.S. DoD applications. The DoDAF is a descriptive methodology for capturing high-level system information using four different display formats or views. "All major DoD weapons and information technology system procurements are required to document their enterprise architectures using the view products prescribed by the DoDAF" (DoD 2007). Figure 4 displays the architectural view categories and their associated relationships for DoDAF version 1.5.

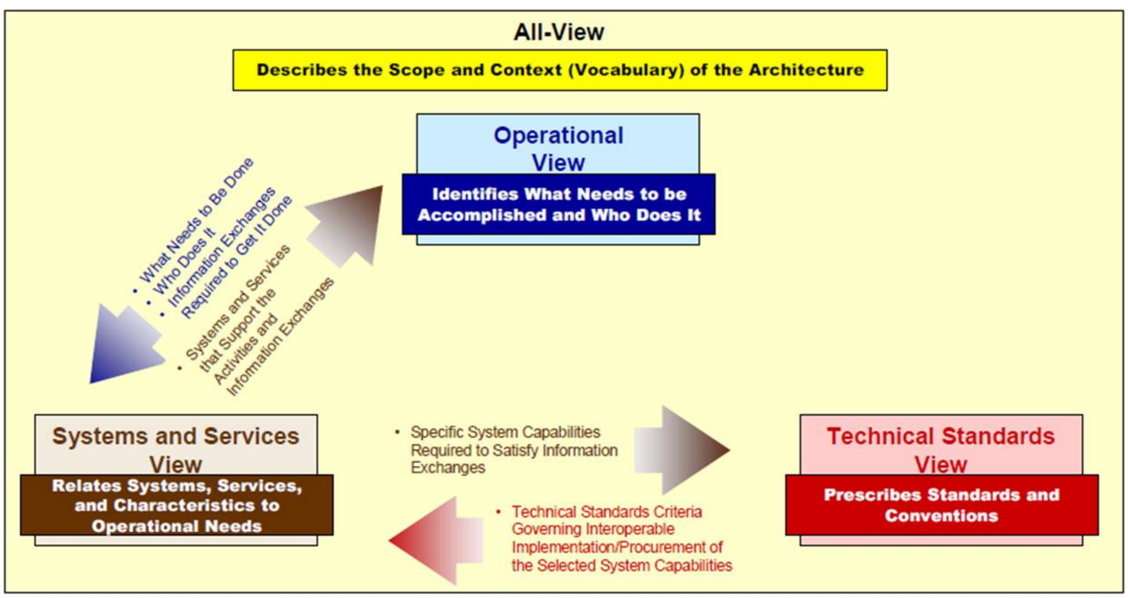

Figure 4. DoDAF View Categories. (From: DoD 2009)

The four DoDAF view sets are (DoD 2009):

- All View (AV): Describes the scope and context (vocabulary) of the architecture.
- Operational View (OV): Identifies what needs to be accomplished and who does it.
- Systems and services View (SV): Relates systems, services, and characteristics to operational needs.
- Technical standards View (TV): Prescribes standards and conventions.

Each view is designed to provide a specific aspect of the system architecture allowing a stakeholder to make informed decisions and changes. The DoDAF uses a shared architecture repository to provide a common language and continuity to the architecture development process. The DoDAF views are defined by Vitech within their Core Architecture Data Model (CADM), which is used to model the capability needs of the UV Sentry unmanned surface vessel. Figure 5 gives specific examples of the four views and brief examples of what they illustrate.

AV-1	Overview and Summary Information
AV-2	Integrated Dictionary
OV-1	High-Level Operational Concept Graphic
OV-2	Operational Node Connectivity Description
OV-3	Operational Information Exchange Matrix
OV-4	Organizational Relationships Chart
OV-5	Operational Activity Model
OV-6a	Operational Rules Model
OV-6b	Operational State Transition Description
OV-6c	Operational Event-Trace Description
OV-7	Logical Data Model
SV-1	Systems Interface Description
SV-2	Systems Communications Description
SV-3	Systems-Systems Matrix
SV-4	Systems Functionality Description
SV-5	Operational Activity to Systems Function Traceability Matrix
SV-6	Systems Data Exchange Matrix
SV-7	Systems Performance Parameters Matrix
SV-8	Systems Evolution Description
SV-9	Systems Technology Forecast
SV-10a	Systems Rules Model
SV-10b	Systems State Transition Description
SV-10c	Systems Event-Trace Description
SV-11	Physical Schema
TV-1	Technical Standards Profile
TV-2	Technical Standards Forecast

Figure 5. DoDAF v1.5 Views Examples. (From: DoD 2007)

b. Naval Architecture Elements Reference Guide (NAERG)

The Naval Architecture Elements Reference Guide (NAERG) and the DODAF provide the standard for defining DoD system architectures. While the DoDAF aids in organizing the system architecture, the NAERG provides the standard terminology to be used when describing system architecture elements. Using standard terminology in system architectures enables the stakeholders to properly communicate, track,

standardize, and refine DoD architectures and their elements. Standardization of architecture development terms and techniques minimizes efforts in the integration of elements within a system, or SoS architecture. The NAERG provides a repository of information critical to architecture framework development and programmatic and acquisition activities. The NAERG includes the Common Systems Function List (CSFL), Common Operational Activities List (COAL), Common Information Element List (CIEL), Common Operational Node List (CONL), Common System Node List (CSNL), and Common System List (CSL).

c. Universal Naval Task List (UNTL)

The Universal Naval Task List (UNTL) is a combination of the Navy Tactical Task List (NTTL) and the Marine Corps Task List (MCTL). It lists tasks that can be performed by naval forces and describes the measures of performance that can be implemented to evaluate individual task performance. The UNTL is used in conjunction with DoD's Universal Joint Task List (UJTL) that contains a hierarchy of joint tasks in support of joint service missions. Both provide a common language baseline and operational reference system for commanders, operators, and trainers. Additionally, both can be used by system designers as an excellent source of requirements, capabilities, and combat activities required to perform military missions. Joint Mission Essential Tasks (JMET) and Naval Mission Essential Tasks (NMET) are activities that operational commanders deem critical to mission accomplishment. Both are listed in the Joint Mission Essential Task List (JMETL) and Naval Mission Essential Task List (NMETL), respectively, and are chosen from the UJTL or UNTL.

Although the UJTL and UNTL are intended to be used by trainers and operational commanders, they provide system designers and architects with a valuable tool in determining capability needs through exploration of required missions and tasks. The lists are used to determine mission requirements by exploring the operations that military platforms are expected to perform. The missions are then used to determine the sets of activities and capabilities required to perform the missions. Tracing operations to the task level provides designers with individual activities that must be accomplished by

a military entity to accomplish the assigned mission. These tasks can aid the system architect in building comprehensive functional and physical architectures. This process also provides designers with operationally relevant terminology and measures of effectiveness valuable to system development. This allows system engineers and architects to design a military system using warfighter terminology, focus, and measures. Using warfighter terminology and mission-derived capability needs allow system designers to better communicate with the DoD customer and to provide them with a more comprehensive product.

5. Design Reference Mission (DRM)

The DRM is a documentation exercise used as a tool to aid in the systems engineering requirements definition process (Skolnick and Wilkins 2000, 208-216). The first step in the concept development process is to fully define the requirements of the desired system. This step ensures the designer effectively defines the problem without a preconceived notion of a particular solution. The DRM establishes the baseline for subsequent systems engineering activities. It establishes the groundwork for the generation of requirements, refining problem definition, development of concepts, analysis of alternatives, and test and evaluation (Skolnick and Wilkins 2000, 208–216). The concept is used to establish a warfighting CONOPS for a system and to describe the operational activities necessary to achieve desired system capabilities.

Composing a DRM begins with understanding the warfighter’s operational concept. This understanding is then used to build a simulated environment in which system concept alternatives are expected to perform. The projected operational environment (POE) is the environment in which the system is expected to operate and provides the context within which tasks will be performed in support of the mission. Once in a mission-executable environment, the capabilities necessary to complete that mission can be exercised. When designing a reference mission, it is important to understand the environment surrounding the mission analysis. A scenario includes a goal, a deployment of systems, a physical environment in which the mission takes place or is executed, and whatever changes the environment will undergo as the scenario progresses.

“The DRM defines the specific projected threat and operating environment baseline for a given force element…” (Skolnick and Wilkins 2000, 208–216).

Operational Situations (OPSITS) are unique instances of a DRM where the variables can change. They are identified based on needs requirements and are meant to feature selected operational characteristics, or combinations thereof, in operationally viable combat environments. OPSITS should be specifically developed to stress selected system design attributes and support functional and performance tradeoff analysis (Skolnick and Wilkins 2000, 208–216). Educated assumptions are made about the operational environment, required logistics, deployment, and mission timeline. The systems engineer must determine which OPSITS are necessary and ensure they are validated by subject matter experts (SMEs).

E. SCOPE

The overall UV Sentry development process in Figure 1 is broad enough to cover the entire system development. The scope of this thesis is limited to the model-based systems engineering and related trade off assessments for a UV Sentry autonomous surface craft designed to serve in a force protection mission. The methods and tools provided present a baseline process for developing the USV systems architecture and model-based tools for concept exploration and tradeoff analysis. The analysis in this thesis does not reflect a finalized conceptual design. The analysis gives a clear picture of the process in a “real world” design application.

The primary focus of this thesis is to provide a systems architecture and conceptual design footing for the UV Sentry SoS unmanned surface vessel (USV) design team. It is to be used as a guideline for system designers and architects and employed when constructing their system-specific MBSE architecture and design methodology. This thesis offers a number of tools and techniques for designers to build a comprehensive conceptual design leading to a successful system design. It focuses on the conceptual design of a USV to provide explicit support to the UV Sentry SoS program

but the methods, tools, and techniques described are not limited to the design of a USV. The process described herein can easily be used in support of any system or process design.

F. METHODOLOGY

Model-based design uses mathematical models and visual aids to guide designers and architects in the development, design, and testing of systems. MBSE is particularly useful for designing large, complex, or highly integrated systems or systems of systems. MBSE significantly differs from traditional design by using models to simulate system performance to appropriately augment the use of expensive and time-consuming prototypes or teams of engineers making multiple performance calculations for each operational scenario. This approach provides system designers with fast, flexible, and efficient tools that can be used throughout system development and test and evaluation.

The process begins by identifying the system (or type of system) to be implemented and finding, or building, a model to simulate the "real-world" system performance and interactions. Once the model is determined to be acceptable, it can be used to analyze predicted, dynamic system performance and synthesized to test system requirements, specifications, and potential shortcomings. Models can be used early in system development providing the means for system designers and stakeholders to explore design concepts by simulating a proposed system point design in its expected operational environment. This allows designers to test ideas without spending large amounts of money on prototypes and physical testing. MBSE also builds a common design environment facilitating effective communication between system stakeholders. Using models early in the development process allows designers to identify and correct design issues before they become too costly to address.

Figure 6 illustrates the simplified model configuration used in the MBSE SoS development process. The SoS architecting model, ship synthesis model, and MCDM tool are each used to build the conceptual design. The ship synthesis model predicts the physical performance of the system. The architecture model includes the framework and

organizational structure for the operational, functional, and physical models. The MCDM tool provides the means for system developers to explore conceptual designs and analyze design tradeoffs.

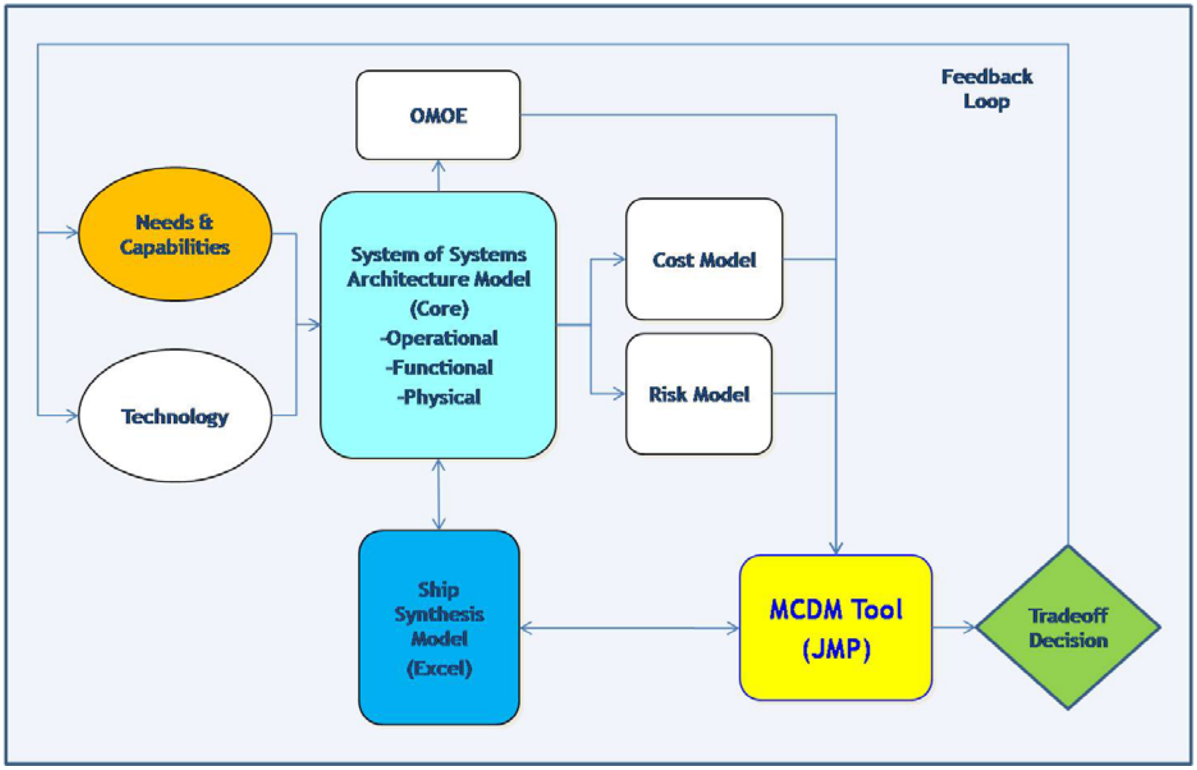

Figure 6. MBSE Method.

Constructing the system architecture for the UV Sentry USV is a cooperative process headed by the system architect that must include all system and process stakeholders. The architect must continually work with the stakeholders to iteratively define the system structure, resolve ambiguity, reduce complexity, and focus creativity toward a problem solution. The architect must direct the transformation of the system from conception to realization by using a series of SE and architecture development tools and techniques. Each step in the process further develops the architecture model increasing system clarity and fidelity with each design iteration. Architecting principles, model-based methods, SE tools, and management activities are used to define, develop, integrate, and evolve the functional and physical models. The architecture model exists to

develop a well-defined system that meets the desired system effectiveness. The system architecture provides the means to model, simulate, engineer, display, and test concepts.

Defining the architecture model structure starts with the transformation of operational mission capability elements into a set of operational activity elements. The creation of the architecture model (the fundamental structure of a system) is the key step in the transformation of loose requirements to a well-structured definition for system development. In the most basic terms, design can be defined as a process to determine form based on function. Creating various concepts through a design process allows engineers to explore the solution space, applying creativity to the development of concepts. The determination of how well each concept accomplishes functional characteristics, as manifested in the physical form proposed, becomes the basis for selection of the best concept solution. This conceptual design process is a critical step in transforming capability needs to physical function. This step allows system designers to explore design alternatives and ultimately select the design that best meets the needs of the stakeholders.

Building a model-based method using the architecture products alone does not provide adequate information for a smooth transition from system development to a more traditional systems engineering process. An Element Relationship Attribute (ERA) structure is a more rigorous method needed to define the architecture model, and provide a structure upon which to make reasoned decisions. The ERA based architecture definition language handles the syntax and semantics needed for creation of the base architecture model and derived products. This includes the ability to enact an iterative process of discovery in meeting emerging capability needs as they arise.

Next, operational activity elements are related to functional, non-functional (constraints) elements, requirement (functional achievement metrics) elements, and other elements. This leads to the eventual specification of component elements that are used to create the finished product. This structure provides the basis necessary to facilitate concept trade-off studies of possible alternatives by explicitly recording the

interconnections among elements. The method allows stakeholders to focus future research efforts and prevent the expenditure of vast resources into non-critical or easily countered areas.

For this thesis, input variables are treated as both uncertain and deterministic to create models based on probability of occurrence. This facilitates more exploratory trade-off studies showing probabilities of achieving outcomes instead of hard boundaries for trade-off. The variables are defined by distributions of possible outcomes, rather than these fixed points, since there is uncertainty associated with their achievement, either due to technology limits or perhaps funding levels need to get them to the limits desired in the time frame desired. This can provide valuable information for technology planning and maturation expectations in the technology development phases of product acquisition. This method also allows stakeholders to tailor the model as the program evolves to account for things such as technology maturation, cost growth, risk assumption, or requirements creep. Specifically, this will be used to determine where to focus technology investments, and what technology development goal is required to achieve the desired outcome.

The systems engineering and architecture development model was implemented using the Vitech CORE systems engineering repository software package. The ship synthesis model is a Microsoft Excel-based ship resistance tool specifically implemented for prismatic planning hulls. Optimal design space exploration was accomplished using Design of Experiments (DOE) and Response Surface Methods (RSM) from ship synthesis model data. This was accomplished using the SAS JMP statistical software package. JMP provided visualization of the model outcomes and the means to accomplish the quantitative trade-off of specific design variables in the context of system measures of performance (MOP).

G. APPLICATION

The methodology described in this chapter is applied in the following chapters to apply a systems and mechanical engineering approach to develop an executable system architecture model for the UV Sentry System’s autonomous surface craft. The MBSE

approach is expanded to a model-based systems engineering concept that uses modeling in both the conceptual design and architecture development process of system development. The architecture model and MCDM tool developed in this thesis provides UV Sentry stakeholders with the means to conduct and prioritize system-level mission and technical assessment studies in developing the framework for the conceptual design.

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II. UNMANNED SYSTEMS

A. INTRODUCTION

Unmanned systems are currently used in a variety of military applications around the world to perform tasks that are dirty, dull, and dangerous for soldiers, sailors, and airmen to perform. They span all domains including air, land, surface, and subsurface applications.

B. OVERVIEW OF CURRENT STATE

Unmanned systems are intended to provide significant reductions in manpower and risk to personnel while providing persistent accomplishment of mission tasks. They are designed for a number of security and military applications with a multitude of emerging capacities currently being developed. Traditional roles for unmanned vehicles focus on the collection and dissemination of ISR information. Future unmanned system capabilities include autonomy, targeting, offensive and defensive fire, and multi-mission applications.

Unmanned vehicles can perform missions in areas deemed unsafe or politically sensitive for human operators. They can be deployed from a variety of platforms and maintained on station as long as fuel and the operational environment dictate. UVs are currently in use all over the world, with particular emphasis on their use in support of operations in Iraq and Afghanistan. Their use has grown significantly in recent years, with increased warfighter demand expected in the near future as more emphasis is placed on cost-effective ways to provide safety and security.

C. PROBLEM WITH CURRENT STATE

Unmanned systems are typically designed and built to perform a single mission and require a robust support element including numerous operators and maintainers. The personnel required to control, launch, recover, fuel, and maintain unmanned vehicles often rivals that of manned systems. Automation of unmanned system functions would ease the requirement for support personnel providing significant savings over traditional

UxV systems. Along with automation, future unmanned systems must shorten the time it takes to refuel and return to station. Autonomous refueling capability coupled with a forward-deployed refueling base permits unmanned vehicles to remain on station longer by shortening refueling transit times. Ultimately, this will further reduce cost by requiring fewer vehicles to perform a given mission by reducing the frequency of on-station reliefs.

Communication and data transfer capabilities pose another significant issue in UxV operation and development, particularly with USVs. Current systems are greatly hampered by the highly restrictive limits of line-of-site (LOS) and over-the-horizon (OTH) tactical links. Military and DoD-commercial communication satellites are currently operating at their maximum bandwidth capacity. Unmanned system communication requirements significantly strain DoD-dedicated satellite assets. Today's USVs typically require human operators to maintain LOS connectivity with the UVs they are controlling. The enormous bandwidth and the high rate of data transfer required are far too hefty for current satellite capabilities. Having to maintain LOS connectivity places the UV closer to the operator increasing the operator's chance of harm. USV automation provides internal control of system functions resulting in a vast reduction of data bandwidth required for operation. This allows the vehicle to operate farther from control personnel, placing the human out of harm's way.

The lack of system collaboration is another significant shortfall in the development of UxV systems. There are a number of current UxV research and development (R&D) and acquisition programs in existence but far less coordination and capability sharing between organizations and their systems. This lack of coordination is a challenge to designers of future multi-mission, multi-domain UxV SoS. Future UxV capabilities must incorporate a fully coordinated, multi-domain, multi-mission SoS to achieve the full benefits of unmanned systems. This system of unmanned systems shall cover all domains and function autonomously within its network-centric area of operations. The systems components shall be able to operate individually or collectively to accomplish an assigned mission. This SoS arrangement maximizes the effectiveness as well as the combat and operational survivability of the system as a whole. If an individual unit is disabled or reassigned, the system autonomously adjusts and assigns other assets

to perform the re-assigned unit's tasks in a prioritized order. An integrated network of multiple unmanned vehicles and external sensors can effectively span large geographical areas greatly improving situational awareness and mission coverage.

D. UV SENTRY

1. Overview

The UV Sentry SoS is an Office of Naval Research (ONR) led initiative investigating the use of unmanned vehicles for force protection. The project is aimed at preventing terrorism and piracy in the maritime domain using a coordinated assortment of autonomously controlled assets including air, surface, and subsurface vehicles. The initiative leverages a consortium of DoD, governmental department, industry, and academic participants including warfare centers, research laboratories, and the Naval Postgraduate School. The proposed system shall, at a minimum, be capable of searching for and identifying potential threats from an adequate reaction distance, discerning hostile from non-hostile entities, interdicting hostile or non-compliant units, and conducting deterrence and, if necessary, threat neutralization actions.

A key near-term project goal is to develop functional architectures for security missions that support the detection and identification of threats to stationary marine platforms. Figure 7 illustrates an example of the UV Sentry SoS used in sea base defense mission. This example includes mine warfare (MIW), anti-submarine warfare (ASW), and surface warfare (SUW) support missions. The stationary high-value asset (HVA) protection mission was selected as a good starting point due to its importance, relevance, and straightforwardness.

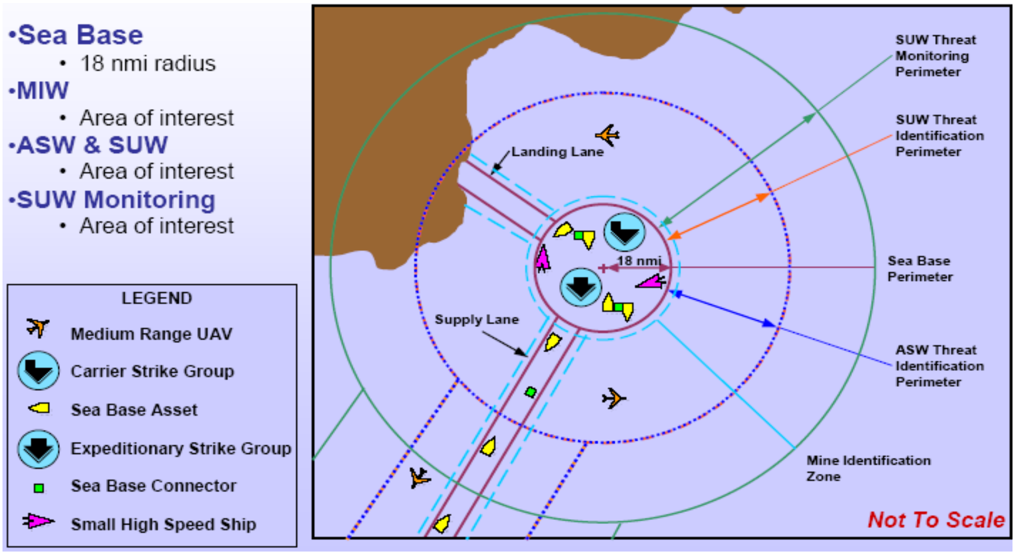

Figure 7. UV Sentry in Defense of a Sea Base. (From: Whitcomb et al. 2008)

2. Need

Sea based assets are highly vulnerable to attack from a number of adversaries with the capability to inflict grave damage. The asymmetrical nature of terrorist attacks and the large coverage areas to protect make the protecting sea based assets particularly challenging. Stationary HVAs, such as ocean oil drilling platforms, are particularly vulnerable and must be protected from a multitude of potential threats including disguised surface units, aerial attacks, and undersea assaults. In addition, the relatively close proximity of most stationary HVA to shore makes their protection an even larger challenge due the rapid identification, interdiction, and reaction times required.

Manned units spend countless hours patrolling their allocated security area attempting to keep potential hostile entities at a safe distance from their assigned HVA. This task requires manned operators to remain alert and diligent despite the dullness of the mission. In addition, the maritime security mission typically requires a large number of assigned personnel to provide full coverage over a large security area. The complement of manpower required to accomplish the mission depends on the size of the security area, the importance of the HVA (including financially and politically), the probability and severity of potential attack, the nature of the threat, and the availability of protection force assets. In addition to operational staff, a cadre of support personnel must

be included for non-operational tasks such as: logistics, maintenance, training, and habitability. The large number of required personnel places huge financial burdens on the U.S. and partner nation security forces.

Protection of HVAs must be accomplished without placing personnel, or other valuable assets, in harm's way. Employment of manned vessels for maritime security places sailors and their ship in potential danger. The surreptitious nature of the threat often compels security personnel to come in close contact with potentially hostile entities. Coming within close proximity of a capable and determined enemy places U.S. or partner nation personnel in tremendous danger. The loss of personnel or valuable national assets, such as U.S. Navy warships, is socially, politically, and financially deplorable. COCOMs are committed to accomplishing mission tasks while maintaining their assets as far from harm as possible.

The diverse nature of potential threats requires assets to search and protect a large geographical area in multiple physical domains (air, surface, and subsurface). This necessitates the need for a distributed, multi-domain, integrated SoS with elements that operate in tandem to protect the HVA. Use of manned assets to meet this need is not only costly but can be dangerous when friendly assets come within close proximity of one another. The use of manned assets also creates integration and communication challenges that can easily result in loss of situational awareness resulting in lapses in security and potential harm to the HVA.

The UV Sentry SoS offers the autonomous, multi-domain, distributed, integrated, force-multiplying effect required to meet future HVA maritime security needs. The unmanned nature of the SoS maintains a high, persistent level of security while maintaining safe distance for human operators and valuable assets. UV Sentry also provides a cost-effective alternative to using a large number of manned assets.

3. Vision/Goal

The goal of the UV Sentry SoS is to provide persistent and effective defense of naval and maritime assets. The SoS must sense, identify, interdict, and deter current and projected threats to sea based assets. Figure 8 illustrates the UV Sentry concept of

operations in an OV-1 view. The view portrays a SoS of unmanned heterogeneous maritime vehicles which operates autonomously and cooperatively for execution of many different missions (Whitcomb et al. 2008).

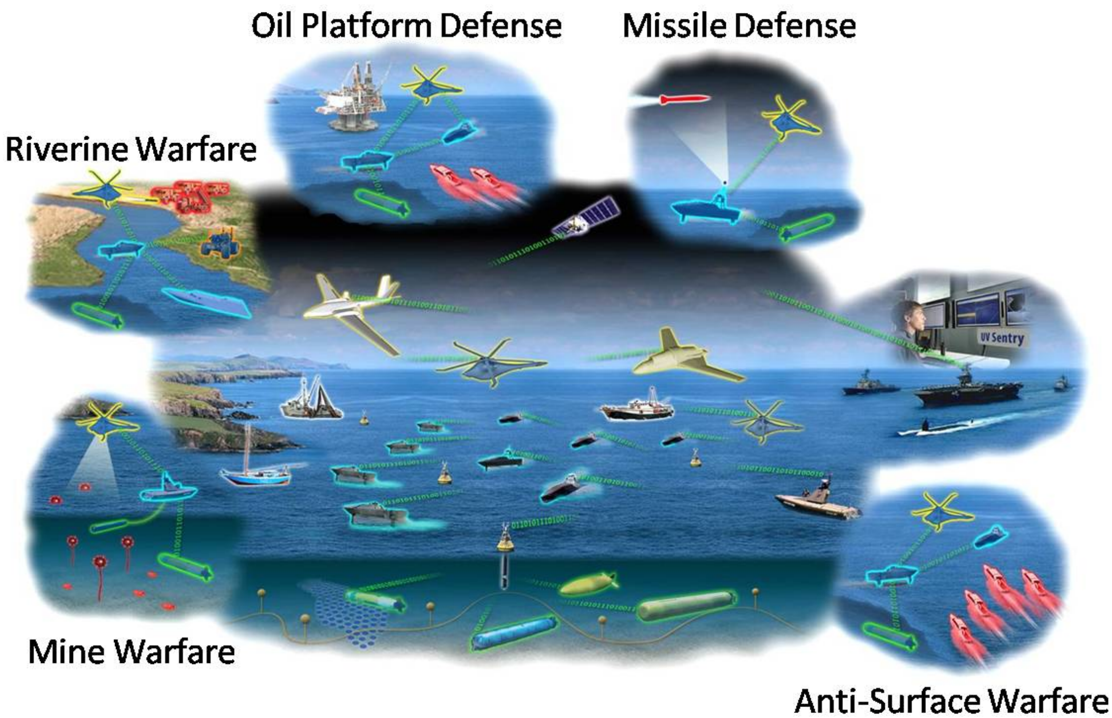

Figure 8. UV Sentry OV-1. (After: Whitcomb et al. 2008)

The UV Sentry vision includes the following capabilities:

- Provide situational awareness around sea-based assets at distances sufficient to neutralize detected threats
- Perform ISR alert function and will, when appropriate, monitor and engage threats
- Operate and manage system assets autonomously, including autonomous refueling/recharging to minimize human supervision/control/support
- Process data autonomously to provide a knowledge base for the operational forces and commanders so that they can make informed decisions
- Deploy non-lethal and lethal weapons under human command and control

E. AUTONOMOUS SURFACE CRAFT

1. Overview

The following section provides a general overview of current USV state-of-the-art. This section provides a baseline understanding of USV mission areas, classes, craft type, component areas, and technical challenges.

2. Mission Areas

The mission areas that are relevant to the USV are: mine countermeasures; anti-submarine warfare; maritime security; surface warfare; special operations forces support; electronic warfare; and maritime interdiction operation support. These mission areas are described below and are obtained from (PEO LMW 2007).

a. Mine Countermeasures (MCM)

"MCM mission requirements are driven by the Fleet's need to rapidly establish large, safe operating areas, transit routes (Q-routes) and transit lanes" (PEO LMW 2007). MCM mission areas can range in size from 100 to 900 nm^2, covering waters all the way to the shore. The objective of the MCM mission is to enable safe Fleet Operating Areas clear of mines.

The traditional MCM functions are: detect; classify; localize; identify; and neutralize. Each of these functions is required to confront the threat that mines pose against Fleet platforms. Additionally, the following MCM behaviors encompass the MCM mission: reconnaissance; search; hunting; breaching; clearance or clearing objective; sweeping; jamming; and signature.

USVs, along with UUVs, are particularly well suited for the "dirty - dull – dangerous" tasks that MCM entails. They provide persistence, which permits significant mine hunting and sweeping coverage at lower cost by multiplying the effectiveness of supporting or dedicated platforms. Additionally, they provide the potential for supporting an MCM capability on platforms not traditionally assigned a mine warfare mission.

b. Anti-Submarine Warfare (ASW)

"It is vitally important that the U.S. Navy be able to achieve and maintain access to all the world's littorals at the times and places of its choosing" (PEO LMW 2007). There are three major categories of ASW as identified by Task Force ASW: "Hold at Risk," "Maritime Shield," and "Protected Passage." "Hold at Risk" observes submarines of interest as they leave a port or in transit through a chokepoint. "Maritime Shield" involves ensuring that a large strike group is not threatened by enemy submarines. "Protected Passage" entails establishing a safe path, free of enemy submarines, for a large strike group.

USVs are able to enhance the ASW mission, specifically, the capabilities of "Maritime Shield" and "Protected Passage." Most of the submarine threats in the future will be from numerous smaller conventional vessels that are able to operate in shallower waters than U.S. Navy submarines can operate. The objective is to utilize USVs to "patrol, detect, track, hand off, or engage" (PEO LMW 2007) enemy submarines. The use of USVs for ASW frees up manned platforms to focus on other mission areas and also enhances situational awareness by extending the sensor reach of the unmanned platforms.

c. Maritime Security (MS)

"MS consists of securing U.S. or allied domestic ports, and protecting ship and maritime infrastructure (piers, docks, anchorages, warehouses) at home and abroad against the spectrum of threats from conventional attack to special warfare [and] specifically target terrorist attacks" (PEO LMW 2007). The key to a successful MS mission is the ability to act on information through good situational awareness. Consequently, Intelligence, Surveillance and Reconnaissance (ISR) are of utmost importance to the accomplishment of this mission. The MS mission is enhanced by the unique capabilities of the USV.

USVs are able to function effectively away from the home platform and in shallow water to enhance sensor information while not putting manned platforms in jeopardy. Furthermore, USVs can operate in areas that are considered to be too

hazardous to manned vessels (both environmentally and militarily). MS system concepts include “sensing, signal processing (for detection, classification, localization, and tracking), decision making (man-in-loop, semi-autonomous, or autonomous), and response” (PEO LMW 2007).

There are seven possible MS USV missions identified. These missions include: strategic and tactical intelligence collection; chemical, biological, nuclear, radiological and explosive detection and localization; coastal and harbor monitoring; deployment of remote sensors; specialized mapping and object detection and localization; non-lethal and lethal threat deterrence; and riverine operations (e.g., civilian boat traffic monitoring). The multi-functionality of USVs and their ability to be deployed from various platforms augment the ISR of U.S. Forces, improving mission effectiveness,

d. Surface Warfare (SUW)

The SUW mission is very similar to the MS mission, however, the SUW mission also encompasses the threats posed in more open waters and littoral regions, and the craft required is more robust. The objective of the USV SUW mission is to “provide the ability to engage targets through the use of lethal and/or non-lethal weapons while protecting or keeping manned platforms out of harm’s way” (PEO LMW 2007). The key capability for the success of the SUW mission is for the USV to be configurable to various payloads as well as the ability to be outfitted with various sensors and weapons.

e. Special Operations Forces (SOF) Support

“SOF units require support for conducting missions involving unconventional warfare, counter-terrorism, reconnaissance, direct action and foreign internal defense, among others” (PEO LMW 2007). SOF is usually used when the goal is to disrupt by “hit and run” and disruption, instead of the conventional “force on force” warfare. SOF support USVs will typically be required to operate in coastal and riverine environments.

The main purposes for using USVs in support of the SOF mission are to complement ISR and to provide transportation and logistic support. The inherent

versatility of the USV increases SOF mission effectiveness and improves situational awareness and SOF logistics through sensor deployment and supply delivery.

f. Electronic Warfare (EW)

The objective of the EW mission is "to use USVs to provide a means of deception, jamming, and warning of electronic attack. USVs can provide a persistent and effective capability with significant range, endurance, and capacity for large payloads and power generation" (PEO LMW 2007). Functions of the EW mission are often dependent on ISR. The USV EW mission encompasses: creating false target deception; acting as a data repeater between large strike groups; and extending radar jamming.

g. Maritime Interdiction Operations (MIO) Support

"MIO is traditionally defined as activities by naval forces to diver, disrupt, delay, or destroy the enemy's military potential before it can be used effectively against friendly forces" (PEO LMW 2007). MIO is inherently a manned mission; thusly, the USV MIO support augments the mission through enhancing situational awareness. The ideal use of a USV for MIO support missions is to provide ISR on a target vessel before a boarding or interrogation. Due to the importance of accurate data and the specialized nature of this mission, emphasis is placed heavily on sensors.

3. Vehicle Classes

The Navy Unmanned Surface Vehicle (USV) Master Plan (PEO LMW 2007) organizes USVs into four classes based on analysis considering USV mission requirements and naval architecture characteristics such as stability, payload, speed, and endurance. Class selection included a weighted scale of USV critical attributes including US Navy ship transportability and minimization of required accommodation modifications. Although these classes are near-term, solution-based USV alternatives, they are briefly described to provide the reader with a functionality baseline and a reference for current design concerns.

a. X-Class

The X-Class is small, special purpose craft intended to be inexpensive and relatively expendable. Vessel length is 3 meters or less and expected to serve in SOF or MIO support missions. They have limited endurance, payload, and seakeeping abilities and are not standardized for modularity. Figure 9 displays a few examples of X-class vessels.

Figure 9. USV X-Class. (From: PEO LMW 2007)

b. Harbor Class

The Harbor Class USVs use a 7 meter RIB as the hull platform to conform with current U.S. Navy ship transportability and accommodation capabilities. The craft has moderate endurance capability and is expected to perform ISR and MS missions. This class is expected to retain the ability for manned operation. Figure 10 displays an example of a Harbor class vessel.

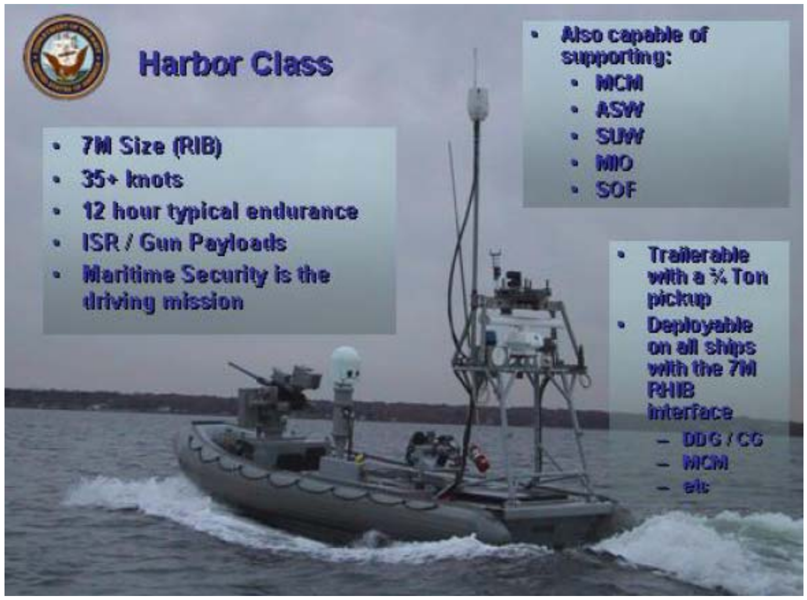

Figure 10. USV Harbor Class. (From: PEO LMW 2007)

c. Snorkeler Class

The Snorkeler Class USV is a 7-meter semi-submersible craft, with only its snorkel above the surface during operation, providing a stable platform in high sea states. This craft is expected to perform MCM and ASW missions due to its ability to pull a tow body and its stability and endurance characteristics. Figure 11 displays an example of a Snorkeler class craft.

Figure 11. USV Snorkeler Class. (From: PEO LMW 2007)

d. Fleet Class

The Fleet Class USV is an 11-meter planing or semi-planing craft providing relatively high speed, extended endurance, and moderate payload capacity. It is expected to perform MCM, ASW, SUW, or EW missions and anticipated to retain the ability for manned operation. The vessel has a modular design with the ability to swap mission modules in less than 24 hours. Figure 12 displays an example of a Fleet class vessel.

Figure 12. USV Fleet Class. (From: PEO LMW 2007)

4. Craft Types

a. Introduction

The Navy Unmanned Surface Vehicle (USV) Master Plan (PEO LMW 2007) also classifies USVs by hull type. These potential alternatives were based on the interface of the vehicle with the sea surface.

b. Semi-submersible Craft

The semi-submersible craft operates with most of its volume below the sea surface exhibiting lower drag and platform motion than conventional hull designs. This results in significantly reduced drag allowing for a larger percentage of the craft's power to be available for other purposes. The craft is less affected by sea state, giving it a larger operational weather window and better sensor and payload stabilization. The platform is very stable making deployment and retrieval of payloads easier. The craft has a very small radar cross section and a low visual signature making it very stealthy. Craft speed is limited to approximately 25 knots for a 7m craft and is more costly than conventional hull designs (PEO LMW 2007).

c. Conventional Planing Hull Craft

There are a variety of conventional planing the V-Hull, Modified V, and M-Hulls. The V-hull is the most common, providing relatively high speeds and a number of positive performance characteristics such as payload capacity and endurance. Planing hulls are more sensitive to load distribution (especially when planing) and may show less towing efficiency than other craft types of its size. At lower speeds (when not in planing mode), these hulls perform similarly to normal full-displacement craft and may be less stable especially in a seaway or when at rest. At high speeds, the hull may experience sea slamming especially in higher sea states or confused seas. Planing craft offer a relatively high payload fraction and can be of low complexity and less expensive than many other hull forms (PEO LMW 2007).

d. Semi-planing Hull Craft

The Semi-Planing hull exhibits lower drag and better moderate speed performance in higher sea states than most conventional planing hulls. The craft typically show less sensitivity to sea state providing a more stable platform for sensors or towing. They can operate at relatively high speeds and tend to be more efficient across the entire array of speeds than most conventional planing hulls. The hull form tends to be more slender with a higher length-to-beam ratio and lower payload fraction than similarly sized conventional planing hulls (PEO LMW 2007).

e. Hydrofoils

Hydrofoils provide the lowest drag and best sea-keeping of all the hull forms making them very stable, especially in moderate to low sea states. They are typically faster than the other hull types due to their very low wetted surface area (when at sufficient speeds), often capable of achieving sustained speeds greater than 40 knots. Hydrofoils are not well suited for towing and are typically more complex than other hull forms making them more costly to design, test, build, and maintain (PEO LMW 2007).

f. Other

There are a number of other conventional and non-conventional craft types that are feasible for USV design. These include pure (full) displacement, Small Waterplane Area Twin Hull (SWATH), wave piercing, and multi-hulls (among others). Each of these tends to be appropriate for very specific capability needs and are not typically used in current USV design. Many of these have a tendency to cost more to design, build, and maintain than like craft and are can be more difficult to transport and accommodate. Apart from the full displacement craft, they are typically more sensitive to weight changes and less stable than other platforms making them unsuitable for most towing and sensor operations (PEO LMW 2007).

5. Component Areas

a. Introduction

The below component areas are essential to the successful completion of all USV missions and are identified in (PEO LMW 2007).

b. Hull

The hull is obviously the most important component of the USV, or of any water vessel for that matter. As discussed earlier, there are many different types of hull design that can be used for the USV, from conventional planning hulls, to hydrofoils. The hull selection is dependent on the mission the USV will be performing. The size of the hull is also a function of the mission type. Typically, USV hull lengths vary from 15 to 40 feet.

c. Ballast

The type of ballast used is dependent on the selection of the USV hull and therefore the mission type. In general, ballast affects a vessels center of gravity and draft. Ballast is particularly important to the semi-submersible hull form because it uses a ballasting mechanism to modify its position with respect to the water line.

d. Energy

Auxiliary power for the electronic components aboard the USV is typically generated by battery or generator or a combination of both. The auxiliary power must be sufficient enough to provide energy for all electronic components on board, such as, actuators for steering, sensors, and communications.

e. Navigation, Guidance, and Control

Navigation, guidance, and control are the "brains" of the USV. Without these elements the USV is simply a boat dead in the water. The essential elements of navigation, guidance, and control are accurate sensors and effective actuators. The sensors that are most important to the accurate navigation and guidance of a USV are the Global Positioning Satellite (GPS) receiver and a radar system. The GPS receiver can interface with a Digital Nautical Chart (DNC) that provides information on permanent obstacles (coastline, piers, buoys, etc.). The standard marine radar (Furuno) is capable of providing adequate data to account for obstacles in motion, as well as correlating information from the DNC to enhance positional location. Sensitive actuators are required to control the USV's steering and throttle based on the environmental picture provided by the sensors. Control modes can either be: "manual," where the actuators are actually fully integrated into the USV; "drive-by-wire," where the helm and throttle have actuators attached to them; and, computer operation, where the USV maneuvers based only on information stored in onboard computer. Additionally, the onboard computer will have to take into account the 1972 International Regulations for Preventing Collisions at Sea (USCG 1972).

f. Communications

The USV must be able to effectively communicate information back to the host platform or possibly other USVs through a network. Additionally, effective communications is required to receive updated instructions. Communication is usually established through line-of-sight (LOS), over-the-horizon (OTH), through a network of USVs, or other relaying assets. A dedicated and hardened communications suite is required to ensure that information can always be relayed to and from the USV.

g. Propulsion

The propulsion system of the USV must provide enough motive force to meet the demands of the specified mission. Propulsion must be adequate enough to optimize maneuverability in various sea states. Additionally, propulsion for full payloads as well as towing must be taken into account. Propulsion can be supplied by either jet drive or propellers.

h. Masts

The mast of the USV must be capable of mounting numerous sensors and communication devices. A key characteristic of the USV mast is modularity, in the sense that the mast can be outfitted to meet the needs of different missions.

i. Auto Launch and Recovery

USV auto launch and recovery requires both organic docking components and an off-platform docking station. The host platform will to be outfitted to accommodate for this function.

6. Technical Challenges

a. Introduction

There are numerous technical challenges that the USV program is confronted with. The following technical challenges as presented in (PEO LMW 2007) will be discussed: autonomy, obstacle and collision avoidance; threat avoidance; automated target recognition (ATR); autonomous deployment and retrieval of untethered systems; and common control. Each of these areas presents unique challenges that must be addressed individually. USV technology will develop in stages in an evolutionary process. Initially, the USV will be run “manually,” or in constant communication with the host platform where decisions are made for the USV. The next step is “semi-automatic,” where the USV will be in intermittent contact with the human controllers for important choices. Finally, the USV will be “automatic,” where it will perform its mission free from human contact, only communicating when mission needs dictate.

b. Autonomy

The issue of autonomy is certainly not one that is unique to the USV mission. Autonomy is the overarching ability that makes all unmanned vehicles unique in their ability to act free of human intervention. An autonomous USV provides many benefits, the two most important being that they enhance situational awareness by extending sensor reach as well as make it possible to reduce manning requirements. There are different levels of autonomy that are associated with the USV, from autonomous maneuvering to autonomous deployment of sensors. To overcome the technical challenges of achieving full autonomy, much research and advances must be made in the fields of artificial intelligence, algorithms, and smart sensors.

c. Obstacle and Collision Avoidance

There are challenges associated with developing a USV that is able to avoid a number of obstacles and other extraneous objects that appear in the environment that degrade mission effectiveness. The USV must have the ability to steer clear of: the shoreline; other vessels; objects above the waterline (for inshore operations); underwater hazards (rocks, reefs, sandbars, etc.); floating debris; and, navigation aids.

d. Threat Avoidance

Threat avoidance is imperative to USVs with missions operating in or near enemy waters. Threats to USVs can appear in numerous forms, including “ships, boats, aircraft, active sensor systems (e. g., radar), and to the extent possible, passive detection systems” (PEO LMW 2007). The challenge associated with threat avoidance is in finding the balance between creating a USV that can avoid threats and damage while not becoming too complex and expensive or degrading the original mission the USV was meant to perform.

e. Automated Target Recognition (ATR)

ATR is a necessary element of obstacle and collision avoidance. Additionally, ATR essential in successfully performing all USV missions (MCM, MS, ASW, and SUW). The challenge associated with ATR is in the development of a reliable

network of on board sensors that provide accurate data that can be integrated and analyzed to create a comprehensive picture of the environment. Ideally, the optimal picture of the environment will be through not only numerous sensors, but also sensors of different types (i.e., radar, optical, infrared, etc.). The key functions of an ATR system are its ability to detect and identify an object accurately. Once sensors that are capable of processing data locally are developed and tested, the ATR challenge will be able to be confronted fully.

f. Autonomous Deployment and Retrieval of Untethered Systems

Autonomous deployment and retrieval of untethered USVs is essential mainly to the MIO Support mission area. This is an area that requires much more development. Technologies such as torpedo and missile launching platforms can be studied and extensively modified to develop a USV variation launching variation. Additionally, as overall USV technology matures, more attention can be given to meeting the challenge of building an affective deployment and retrieval system.

g. Common Control

The envisioned future of autonomous unmanned vehicles involves systems of systems operating in conjunction with one another to fulfill a common mission. Common operational functionality between UxVs in a system of systems sharing communication circuits and sensor networks stresses the need for an open architecture design to facilitate commonality amongst all UxVs. This allows for modularity to support multiple mission areas, ease of logistics, life cycle cost savings and directed technology efforts. The key to meeting this challenge "is in establishing standards for interoperability, communications, Hull, Mechanical, [and] Electrical (HM&E) and payload modularity, and Command Control, Communications, and Computers (C4) architecture.

F. SUMMARY

Chapter II provides a general overview of current USV state-of-the-art including mission areas, classes, craft type, component areas, and technical challenges. This

overview provides a sufficient knowledge base for understanding some basic concepts and concerns in USV design and implementation. Chapter III describes a proposed process to aid in the transformation of capability needs to conceptual design for the UV Sentry USV design tools used to build the MCDM model.

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III. DESIGN TOOLS

A. INTRODUCTION

The MBSE process is intended to provide engineers with a structured method for system architecture and design development. The method aids the iterative SEP by providing engineers and architects with the framework and tools necessary to organize, manage, track, modify, and test system design. This chapter describes the tools and methods proposed for developing an architecture and designing an autonomous USV in support of a UV Sentry mission. It describes the elements and method for the proposed MBSE, architecture development and decision-making process to aid in the transformation of capability needs to conceptual design for the UV Sentry USV.

B. METHOD

The SE process depends on cooperative innovation and iterative advancements to yield a comprehensive system that meets customer requirements needs. The key to success in the conceptual design lies in the efficient and effective transformation from needs to functions and from functions to physical realization. This transformation can be very problematical in a complex system especially when using traditional engineering and architecture development methods. The magnitude of the capability needs, the elaborate technology involved, and the intricate relationships between system elements make designing an autonomous USV particularly difficult. It is imperative that stakeholders maintain traceability and control through every step of the development process and through each iteration of the proposed design. It is also critical to use a series of methods and tools that enable stakeholders to communicate ideas, analyze tradeoffs, and determine and agree upon optimal designs.

The method uses several tools including a ship synthesis model, an architecture model, and a multi-criteria decision-making model to organize, construct, and transform the system design. The three models are intended to be used concurrently throughout the UV Sentry SEP to continually improve design comprehensiveness and fidelity. The ship synthesis model is the “physical” model used to predict expected performance

characteristics in a simulated operational environment. The architecture model provides the structure and organizational means to build the various views of the system architecture. The MCDM model uses the static output data from the ship synthesis model to build a dynamic decision making tool to be used for concept exploration and trade-off analysis. This model enables stakeholders to visualize the feasible design space facilitating effective project communication and decision making. The MCDM tool uses DOE and RSM to form a regression model from ship synthesis data to build the visualization and analysis tool. After making decisions based on MCDM analysis, project stakeholders will make the appropriate updates to the architecture model. Stakeholder decisions and new developments, such as constraints or technology maturation, may also force changes to the ship synthesis data. When this happens, the designer makes the appropriate changes and re-runs the model for the next iteration. With every step the design development gets closer to solving the design problem and meeting stakeholder capability needs.

C. SHIP SYNTHESIS MODEL

1. Overview

The ship synthesis model is the heart of this model-based design process. It provides the "physical world" predictions that are then combined to build the conceptual design space. Properly capturing the design space is essential to useful and accurate concept exploration. The old adage, "garbage in, garbage out," applies when it comes to exploring the design space. An inaccurate synthesis model will yield an unsuccessful view of the design space. This skewed view could lead designers down the wrong road in the system development process resulting in a less than optimal design. The importance of choosing the appropriate ship synthesis model cannot be expressed enough. Ship design engineers need simple and relatively accurate estimation tools for predicting ship performance. There are countless models to choose from, each with their own respective capabilities and limitations. System developers must work with stakeholders to ensure

system capability needs are properly defined before choosing the synthesis model, or models, used. Designers must also periodically re-evaluate their model(s) as iterations in the SE process develop.

Ship synthesis models typically involve a combination of empirical data, theoretical calculations, and experience-driven rules of thumb to determine physical predictions. Every synthesis model uses its own assortment of inputs, assumptions, data, and calculations to provide its user with output information. Predicted ship properties such as hydrodynamic resistance or displacement are projected to find valuable second and third-order predictions like required power or endurance.

2. Model Selection

Recent developments in high-speed craft have created many different alternatives to the traditional full-displacement monohull craft. Hull type selection is a critical issue in preliminary ship design. Selection of hull form requires a great deal of investigation and analysis beyond the scope of this thesis. Attributes such as lifecycle cost, performance parameters such as speed and seakeeping, and manufacturability must be factored into the overall decision process when choosing a hull form. Planing monohulls are very popular for use in autonomous surface vessels due to their potential for high speeds compared to traditional monohull craft. For this reason, the planing monohull was chosen for the ship synthesis portion of this thesis' model-based design.

The model chosen is an Excel model used by naval architects at Naval Surface Warfare Center (NSWC) Carderock's Combatant Craft Division (CCD). The model uses data and calculations from Daniel Savitsky's *Hydrodynamic Design of Planing Hulls* (Savitsky 1964, 71–95). The technique, often referred to as the "Savitsky method," is a relatively simple but comprehensive hydrodynamic power prediction method based on experiments conducted on prismatic planning hulls.

The model is only applicable for high-speed, prismatic, chine hulled vessels in the planning condition. At slow speeds, planing-hulled craft performance characteristics approach those of traditional displacement monohull vessels. Non-prismatic planning

hulls can be considered "prismatic" in high-speed operation mode. The model equations cover a variety of lift and drag forces such as normal force, friction drag, and spray drag.

The model uses Savitsky's "short form" calculation method due to its relative ease of use and comprehension. This form assumes all relevant ship forces pass through the center of gravity (LCG) in calculating a vessel's resistance. Although this method is not as accurate as the "long form" calculation, it is perfectly acceptable as a performance prediction model, especially during conceptual design.

3. Model Variables

The ship synthesis model is comprised of a number of input and output variables applicable to designing relatively small, high-speed, planing craft. The model inputs consist of vessel physical characteristics, performance capabilities, loading parameters, and environmental conditions. Figure 13 displays the ship synthesis model and associated inputs and outputs. The inputs (and units) are: vessel length (feet), deadrise (degrees), LCG (%), and velocity (knots), percentage of cargo (%), percentage of fuel (%), headwind speed (knots), and average wave height (feet). All inputs may be manually typed or dialed in using a visual slider via mouse (macros enabled). Model outputs include (and units): required shaft horsepower (SHP), maximum duration (hrs and NM), estimated lightship (LBS), and maximum cargo (LBS). These values change automatically when the slider is moved or a new value is entered into a respective input cell. The model also includes a graph of required power versus speed with lines for minimum and maximum power depicted and labeled. The location of each set of input values is displayed as "input vessel" on the graph. This gives the user a visual reference of where an individual point design lies on a plot of required SHP vs. maximum speed.

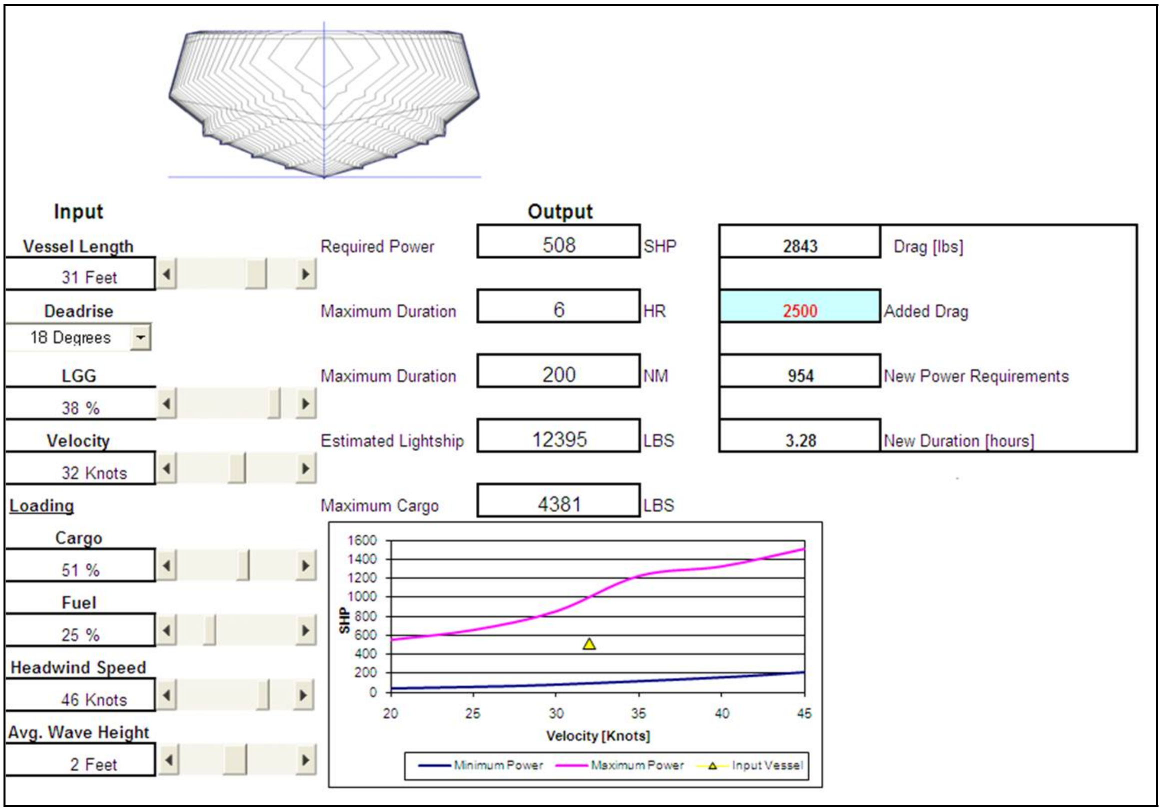

Figure 13. Ship Synthesis Model.

4. Limitations

Speed is an important characteristic of both manned and unmanned sentry craft. A ship's ability to increase velocity over an adversaries' maximum speed can be the difference between preventing an attack on a high value asset and allowing a threat to enter an exclusion zone. In general, two principal forces limit speed improvements of surface vessels; aerodynamic and hydrodynamic drag. Of these forces, hydrodynamic drag, or the resistance of the water on the wetted surface of the hull, is the primary hindrance of increasing speed in ship design.

Reducing hydrodynamic drag, streamlining the wetted surface of the hull (to minimize turbulence), and increasing the power-to-weight ratio of the vessel are the most popular methods of increasing a ship's capability to increase speed. Unlike normal displacement hulls, planing hulls use hydrodynamic lift in addition to hydrostatic lift or

buoyancy. Hydrodynamic lift raises the hull, reducing the wetted area of the hull, allowing the vessel to act as a hydroplane at higher speeds. At slow speeds, a planing craft performs like a displacement craft. As speed is increased, the relative motion between the hull and the passing air and water causes a hydrodynamic lift on the bow. This upward force results in the aforementioned reduction of wetted surface area and a corresponding reduction in hydrodynamic drag thereby increasing craft speed.

At planning speeds, a typical planing hull generates large amounts of waves and spray adjacent to the hull when at planing speeds. The physical action of the waves and spray are very difficult to predict, adding a great deal of uncertainty to any planing model. In addition to wave making uncertainty, air resistance plays a larger role in model uncertainty due to the higher speeds and hydrodynamic forces involved with planing craft. Aerodynamic hull factors have considerable influence on overall resistance, and performance, of planing craft. The model addresses wave making and air resistance uncertainties by allowing the user to enter headwind speed and average wave height. Entering headwind and wave height information helps improve model accuracy but only applies loose estimations of wave and wind effects on ship performance.

Appendages also typically add to hull resistance and a corresponding reduction of speed and efficiency. Bilge keels, propellers, struts, shafts, and sensors (e.g. SONAR) are examples of appendages that add to model uncertainty. The model includes a separate section that allows the user to add an estimated value for combined vessel drag. The section contains value cells for “new power requirements” and “new duration,” in hours, that correspond with the added drag. This enables users to account for adding to or increasing the size of hull appendages. The vessel drag function improves model utility but must be used with caution as it is based on loose estimates of drag and assumes near ideal sea surface conditions.

Calculating ship draft for planing hulls is difficult across the full spectrum of ship speed. The draft of normal displacement craft is a function of full load displacement, length, beam, max section coefficient, and prismatic coefficient. A planing craft at high speeds adds model uncertainties, due to hydrodynamic forces, to the draft estimation.

These uncertainties result in subsequent wetted surface and resistance calculation uncertainties that detract from model fidelity and add to model limitations.

Elements such as vessel trim, shallow water bottom effects, and seaway effects typically effect craft performance and are not accounted for in the model. These effects add a greater amount of uncertainty to the model further limiting model fidelity. Correction factors normally required for non-prismatic (warped) hulls are also not accounted for in the model. The combined effects of all of the aforementioned uncertainty detract from model accuracy but do not discount the usefulness of the model. The short-form Savitsky calculation model is a good starting point to study the conceptual design space. There are models that estimate hull performance derived from the Savitsky long-form equations and more accurate calculations based on better hull form, appendage, and environmental condition inputs. These models are typically more difficult to operate and understand, often clouding the truly important design concerns. The designer must study all available ship synthesis models and determine which best fits the particular type and stage of system design.

D. ARCHITECTURE MODEL

1. Overview

The Vitech CORE software analysis package was used to model the UV Sentry USV SoS architecture framework. CORE is a unified system architecture development tool that provides the means to integrate the model-based systems engineering process, DoDAF structure, NAERG terminology, and SoS architecture development process into an integrated package. This allows system architects to define, design, and build a complete, useful, and usable system; while lowering risk and engineering support costs (Vitech). This tool facilitates architecture development and ensures system elements are comprehensive and consistent throughout the design process. The system functions within CORE are derived directly from the Naval Architecture Elements Reference Guide (NAERG) as a predefined list of functions for combat, infrastructure, and logistics

(Whitcomb). Consistency and traceability are effectively maintained due to CORE's interactive development, and continuous correlation, of operational, functional, and physical architectures.

The architecture is divided into two behavioral domains: operational architecture and system architecture (Vitech). Figure 14 illustrates the CORE architecture development schema showing the system and operational architecture domains along with their respective elements and associated relationships. The operational architecture domain primarily consists of evaluating concepts and capabilities while the system architecture domain describes the requirements, functions, and components that make up the physical design (Vitech).

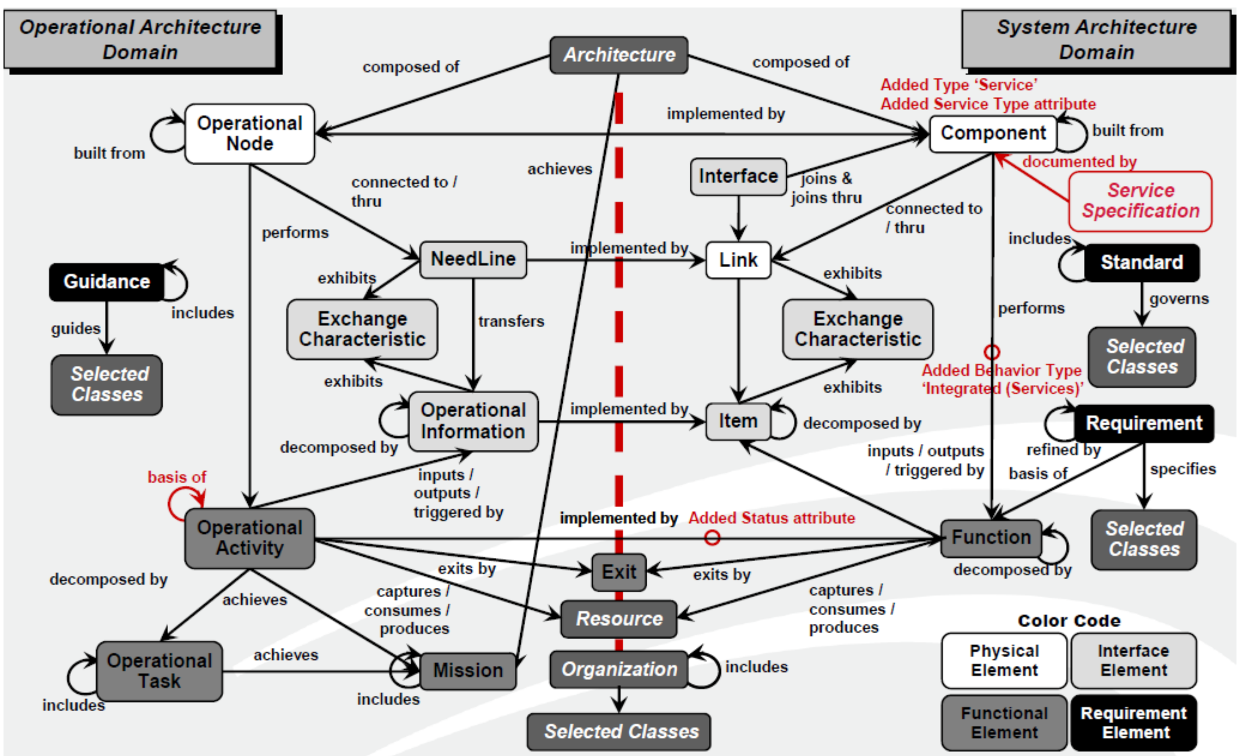

Figure 14. CORE Architecture. (From: Vitech Corporation 2009)

CORE is used to capture and coordinate operational, functional, and physical models in order to construct an integrated architecture (Vitech). The three are described as follows:

- Operational models reflect how system elements perform operational activities, interactions among the activities, the sequence of operation of the activities, and performance and timing associated with the activities (Vitech).

- Functional models reflect function decomposition, data flow among functions, the sequence of the functions, resource utilization, and performance and timing associated with the functions (Vitech).

- Physical models reflect platforms, facilities, operational nodes, systems, personnel, and interfaces (Vitech).

In the design and development phases of a program, systems development activities often fall into four activity domains—requirements, behavior, architecture, and Verification and Validation (V&V) (Vitech). CORE concurrently synchronizes the development of all four domains to ensure consistency and integrity between the domains allowing the architect to locate and correct domain discrepancies. Figure 15 shows the four domains and their interactions within the CORE construct.

The MBSE process coupled with the CORE structure allows system architects and designers to effectively communicate ideas, with common language, to the various stakeholders. CORE deliverables include DoDAF "standard" views (AV, OV, SV, and TVs) each representing a different stakeholder perspective. Documentation artifacts are derived from the developed architecture and include hierarchical decompositions and a multitude of graphical displays to exhibit data. The output is a fully developed and integrated system architecture that contains specifications, design, and interface documentation.

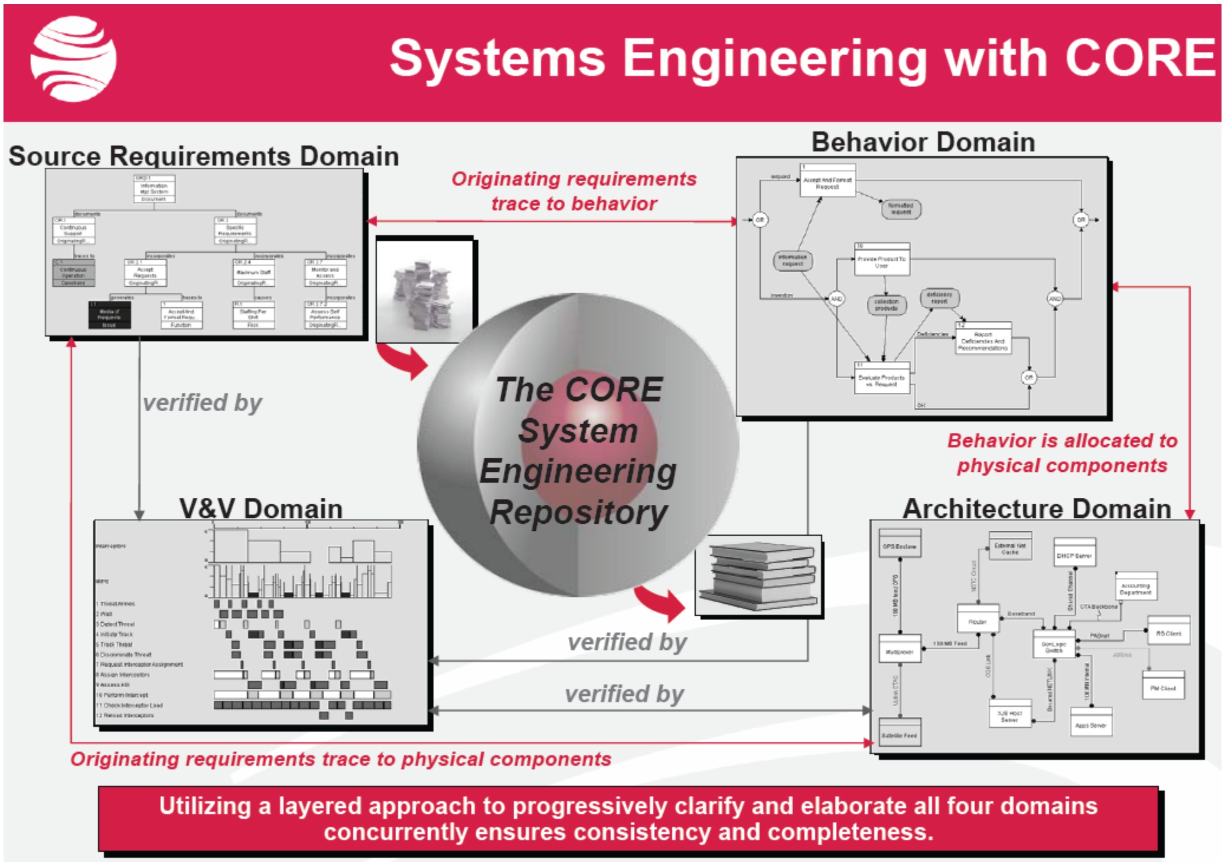

Figure 15. CORE Domains. (From: Vitech Corporation 2009)

2. Design Reference Mission Example

a. Introduction

A notional USV mission was explored to demonstrate how the DRM process can be used to help build the system architecture. A basic DRM was constructed for an autonomous USV in an oil platform defense mission. It describes the background, mission, threats, environments, and a tailored Operational Situation (OPSIT).

b. Background

A relatively tight margin exists between global oil production capacity and global consumption. Stable collection, production, and distribution of oil and natural gas are essential in maintaining the global economy. The threat of terrorist attack is a very

real threat to both the oil and gas field installations and to the transportation and distribution systems connecting petroleum fields to the markets. The threats of attack have resulted in higher market prices for crude oil and natural gas. These threats place a great deal of emphasis on oil companies and national and international authorities in oil platform security. This vulnerability makes offshore facilities an attractive target for insurgent organizations seeking to attack developed world economies.

Unmanned systems are highly utilized in today's military and are increasingly sought after for future military operations. Combatant Commanders (COCOMs) are asking for unmanned vehicles with ever-increasing capabilities to perform tasks that are considered dirty, dull, or dangerous for manned platforms. These tasks include: surveillance and reconnaissance; signals intelligence (SIGINT); mine detection; force protection; homeland defense; irregular warfare; and conventional campaigns. Unmanned systems have an unbounded potential to provide an affordable force multiplier to U.S. military and law enforcement.

The next step in the technological development of unmanned systems is in the transformation from remotely operated, limited task unmanned systems into autonomous, multi-mission systems. In addition, greater efficiencies and improved interoperability could be achieved via an integrated, multi-domain, holistic approach to unmanned system design. The UV Sentry program seeks to identify how unmanned systems can be optimized to support a greater set of mission areas, identify those common areas of technology maturation that can lead to performance improvements in all domains, and identify the technology enablers needed to foster the ability to conduct collaborative operations between multiple unmanned systems in multiple domains.

c. Mission

In general, autonomous USVs are desired to perform missions that require capabilities such as:

- Persistent, wide area surveillance, tracking, and interdiction capability
- Target discernment in a congested littoral environment

- ISR capability in potentially dangerous areas
- Multi-domain detect-to-engage capabilities
- Automated data fusion into a common operational picture (COP)
- Autonomous identification of suspect vessels

In a security role, the Autonomous USVs must persistently search, detect, and identify suspect vessels, to a high degree of confidence, within a large amount of background shipping and aircraft. This mission is comprised of three main phases: Surveillance, Detect and Identify, and Intercept and Engage.

The Surveillance phase consists of using area surveillance and autonomous collection and fusion of embedded and external sensor data to search for potential security hazards. This phase includes autonomous task distribution between the various platforms to ensure the most efficient and effective combination of assets is utilized. In addition, sensor data will be networked and fused to maintain a continually updated COP. This phase also includes automated launch, recovery, and refueling of the USVs allowing the required fleet to remain on station for the appropriate endurance to perform the mission. The biggest challenge is in discerning suspect vessels amongst a sea of legitimate background marine traffic.

The Detect and Identify phase detects contacts of interest (COIs) for further investigation. Identification data is used to develop track histories and is matched against various onboard or external databases. Tracks without appropriate data or otherwise of interest are passed to unmanned surveillance systems for additional scrutiny. Based on the initial screening, USV develops surveillance tracks and calculates intercepts for COIs. If required, a human can be included in the loop to approve or disapprove intercept plans. Intercept and close-in surveillance vessels are then autonomously, or by human command, launched or directed toward the point of intercept. Automated systems route vehicles to the intercept point and establish close in surveillance of the COI. Input from multiple sensor and data sources is processed and fused to develop a detailed understanding of the target. Based on developed target data, a decision on further

prosecution of the target may direct the vessel to: continue surveillance, end surveillance, direct manned intercept, for search, seizure, or arrest, or direct engagement with unmanned system lethal or non-lethal capabilities, if security environment demands and ROE permit.

In the Intercept and Engage phase, unmanned platforms using various sensors including radar, EO/IR, and acoustic, to process, fuse, and verify target identification information upon intercept. The USV will utilize onboard and external assets and databases to support detection, tracking, identification and intercept. The vessel will intercept and track contacts of interests, autonomously launching and retrieving unmanned vehicles to backfill tracking vehicles as required due to refueling considerations. If it cannot track the COI due to speed, fuel, or geographic limitations, it will autonomously notify external commands of the targets location, course, speed, and altitude, if necessary, for intercept by other platforms or for early warning of an imminent attack. Manned assets may be used to intercept, board, inspect, detain, or neutralize threat platforms. UV Sentry will seamlessly integrate with these manned vehicles, providing operators and decision makers with information during transit to complete the intercept. Wide-area sensor platforms such as aerostats, aircraft, towers, or buoys, can provide automated communications relays.

In an oil platform security mission, UV Sentry assets typically maintain a zonal defense structure made up of concentric area rings extending outward from the oil platform or field requiring protection. The outermost zone, or surveillance zone, typically extends to between 6,000 and 8,000 meters from the HVA. In this zone, the USV (and support assets) autonomously detect and track all contacts that enter the area. The next zone, or warning zone, typically extends to between 2,000 and 4,000 meters from the HVA. In the warning zone, the USV will autonomously warn all contacts they are about to enter the exclusion zone where they will be engaged. The closest ring, or exclusion zone, typically extends out to approximately 2,000 meters from the HVA and marks the threshold where the USV will interdict and potentially engage all known threats. The USV autonomously allocates assets to specific tasks, which include surveillance, interdiction, and warning. Elevated sensors can be used to provide radar coverage and

communication relays for the Area of Responsibility (AOR). At a minimum, radar coverage is designed to locate and track all surface and air tracks in the surveillance zone. Acoustic sensors can be utilized to provide location and tracking data for sub-surface contacts in the surveillance zone. Radar and sonar coverage will be achieved by integrating networked assets including: aerostats, towers, buoys, manned or unmanned aircraft (with radar or dipping sonar), undersea sensors, manned or unmanned surface or subsurface vessels, etc. Data from these distributed multi-domain sensors is automatically fused to form a COP, which provides manned and unmanned operators with situational awareness and the means to allocated assets and make engagement decisions. Automated launch, recovery, and sustainment capabilities permit the craft to remain persistent in the surveillance zone. Sensors deployed throughout the area of interest detect COIs out to just beyond the surveillance zone. These COIs are tracked and when unusual patterns are detected, such as speed increases, lack of Identification Friend or Foe (IFF) or Automated Identification System (AIS), and when they enter the surveillance zone, an asset is allocated to interdict. Manned operators remain in the loop to monitor, and when required, approve/disapprove UV Sentry actions. In addition, unmanned intercept and close-in surveillance vehicles are launched, and later recovered, through UV Sentry automated launch, recover and sustainment systems…

d. Threats

Threats to offshore facilities may come from a multitude of sources in the air, surface, or sub-surface domains. Adversaries intent on destroying or disrupting oil production for political or financial means are highly capable of inflicting major damage to the vulnerable oil industry. Marginally successful attacks can affect world oil prices and destabilize nations. A highly successful attack could result in significant economic and environmental damage. Adversaries can include state-sponsored militants, international terrorist organizations, domestic terrorists, or separatist organizations. The threats to oil platforms and infrastructure are asymmetrical in nature requiring persistent, highly capable systems and processes. Specific threats include:

Air Domain:

- Civil aircraft (armed attack or suicide bomber)
- Armed UAV
- Cruise missiles

Surface Domain:

- Armed Attack Boats (machine guns, RPGs)
- Suicide Boats
- Armed USVs

Sub-surface Domain:

- Submarines
- Semi-Submersibles
- Armed UUVs
- Swimmers
- Torpedoes

The most probable attack is likely to be from an explosive device onboard a small service or pleasure craft boat. This attack method could prove particularly difficult to defend if a Platform Supply Vessel (PSV) is used as an attack vector.

e. Environment

The offshore environment presents a difficult challenge for maritime forces. Persistent surveillance and response area may span thousands of square miles to protect hundreds to thousands of dispersed individual platforms. The traffic density of legitimate commercial traffic near oil field exclusion zones makes the environment particularly challenging to protect. The proximity to civilian and military air traffic routes, commercial sea lanes, fishing areas, and land make detection and identification of potential foes a huge challenge. The enemy can disguise or hide vessels among a background of commercial and pleasure traffic. The sheer number of platforms, large area to be protected, magnitude of background air and surface vessels, political and legal considerations, proximity to land, and littoral maritime conditions make the projected operational environment (POE) particularly challenging to security forces.

Environmental conditions that must be monitored and considered include:

- Temperature
- Precipitation
- Visibility
- Wind
- Sea state
- Weather (including dust/sand storms)
- Undersea acoustic conditions
- Radar propagation *(ducting, etc.)*

The political and legal environment must be carefully considered including:

- Rules of Engagement (ROE)
- Host nation sensitivities and restrictions
- International/maritime law
- Business/financial considerations

The USV shall operate in both open ocean and littoral waters in the warm waters of the Gulf of Mexico or the Persian Gulf to the cold waters of Alaska or the North Sea. Water temperatures range from 98 degrees Fahrenheit in the Gulf region, to 45 degrees Fahrenheit in the extreme northern and southern oceans.

f. Operational Situation (OPSIT)

(1) Overview. This section presents a brief example of an OPSIT used to help identify capability needs for a UV Sentry USV operating in an oil platform defense mission in the fictitious partner nation of Manitobi. An OPSIT can be a vague or detailed as its author sees fit to convey the idea and be useful for analysis. Some sections are purposely incomplete in the interest of brevity.

(2) Situation. The Manitobi Liberation Army (MLA) is a growing terrorist organization with the knowledge and the means to inflict major damage on an oil platform. The organization is determined to destroy or disrupt oil production and distribution for the country of Manitobi. The government of Manitobi is a budding democracy attempting to rebuild the nation after an intense civil war. The small nation-state is in desperate need of the profits it gains through its international oil sales from its only operating oil platform M36. The platform is two miles off the coast of Manitobi on a recently discovered oil reserve below the ocean floor. The nation to the north of Manitobi is a major shipping port in the region. The country to the south is a vacation destination harboring 20-30 cruise ships each week along with a large number of pleasure craft for fishing and sailing. Many of Manitobi's people rely on fishing to earn a living. The combined effect of merchants, pleasure craft, and fishing vessels make platform security a major challenge. In addition, the platform's proximity to land and other nations make security a time-sensitive task. The U.S. has committed to defend M36 but assets are spread thinly throughout the world.

(3) Mission. Protect the M36 platform from a MLA attack. Use a 6000m surveillance zone, a 4000m warning zone, and a 2000m exclusion zone.

(4) Risk. Grave economic, political, and security setbacks if oil production is disrupted. Region destabilization could result.

(5) Employed Assets. The U.S. Navy employed a network of sensors and USVs to protect M36. There are eight USVs each with a docking station attached to the platform. The aerial radar coverage is provided by an aerostat attached to the North corner of the platform deck. Sonar coverage is provided by a series of disbursed bottom tethered buoys and the USV's organic Sonar system. The U.S. Navy sent a crew of eight sailors to oversee the mission. The sailors monitor the USVs and can interdict, board, search, seize, and engage an enemy vessel using the team's 11-meter manned vessel with a bow-mounted .50 cal machine gun. The operations center is located on the M36 platform deck and requires one manned watch stander present at all times.

(6) Scenario. The Radar aerostat detects three inbound surface vessels crossing into the surveillance zone on a course toward the platform base at

approximately 30 knots each. IFF and AIS sensors determine the vessels are not identifying themselves as friendly, or vetted, craft. The UV Sentry system dispatches three USVs toward the inbound vessels for interdiction and identification. As the USVs close on the suspect vessels, the three vehicles rapidly open the distance from one another in an attempt to confuse the USVs. UV Sentry interdiction algorithms recognize this maneuver and command each USV to interdict a separate COI. The USVs meet the inbound COIs near the warning zone and issue verbal warnings and close-in maneuver…

(7) Summary. An OPSIT is entirely dependent on the intended mission and does not have a specified length or format. In this case, the OPSIT described a situation, mission, risk, employed assets, and scenario. The descriptions were included provide an example of an OPSIT and to show how it can be used to help identify mission essential tasks and required capabilities.

3. Mission Thread

a. Overview

A thread is a mission-specific product that describes the basic tasks required to perform a mission function. Mission threads can be derived from OPSITs in the DRM to help develop test cases for specific system functions. The mission thread provided was developed to show a USV-focused example of how a DRM, OPSITs, and threads can aid in building the initial (before iteration) functional architecture.

b. Thread Description

A USV patrolling an established protection perimeter is continuously collecting, monitoring, and fusing sensor data to maintain the common operating picture. Among its other sensors, the USV uses ES equipment and an IFF/AIS transponder to help ID the COI as friend or foe. The USV identifies a vessel as a suspect COI due to its course, speed, and radar emission frequency. The USV alters course and speed to intercept the suspect vessel. As the COI alters course and speed, the USV reviews and evaluates the ever-changing situation and acts accordingly. The USV also communicates with all required assets and entities while navigating toward the suspect COI. As the suspect COI ignores warnings and enters the exclusion zone, the USV processes the COI

as a target. After the USV gains permission to engage the inbound COI, the USV's lethal or non-lethal assets are employed to stop the suspect COI.

c. *Thread Navy Tactical Tasks (NTAs)*

The following tasks correspond to the thread description in section 3-b and the example OPSIT in section 2-f.

- NTA 6.3.1.5 Establish and Enforce Protection Perimeter
- NTA 2.2 Perform Collection Operations and Management
- NTA 5.5.4 Conduct Electronic Warfare Support (ES)
- NTA 6.1.1.3 Positively Identify Friendly Forces
- NTA 5.2.1.1 Review and Evaluate Situation
- NTA 5.1 Acquire, Process, Communicate Information, and Maintain Status
- NTA 1.2 Navigate and Close Forces
- NTA 1.4.7 Enforce Exclusion Zone
- NTA 3.1 Process Targets
- NTA 3.2 Attack Targets

The tasks were mapped to their warfighter MOEs in the NTTL and were assigned applicable MOPs. Tables 1, 2, and 3 summarize the tasks, MOEs, and related MOPs. The MOEs are developed in warfighting simulation and the MOPs are determined from the USV system component architecture model.

Tasks	Measures of Effectiveness (MOE)		Measures of Performance (MOP)
	Units	Measures	
NTA 1.2 Navigate and Close Forces			
	Knots	rate of movement.	Speed
	Percent	of maneuver force concentrated at decisive point prior to detection.	Speed
	Percent	of supporting force concentrated at desired point prior to detection.	Speed
NTA 1.4.7 Enforce Exclusion Zone			
	Number	vessels located.	Speed/Endurance/Payload
	Number	vessels identified.	Speed/Endurance/Payload
	Number	vessels boarded.	N/A
NTA 2.2 Perform Collection Operations and Management			
	Percent	of targets accurately identified.	Payload
	Percent	of targets accurately located.	Payload/Endurance
	Percent	of PIRs have at least one source that yielded intelligence information.	Payload
NTA 3.1 Process Targets			
	Percent	of desired results achieved by expected conclusion of a given phase or time line.	Payload
	Percent	of selected targets have accurate coordinates available.	Payload
	Percent	of targets susceptible to non-lethal kill allocated to non-lethal attack systems.	Payload
NTA 3.2 Attack Targets			
	Percent	of missions requested by components executed.	Speed/Endurance/Payload
	Percent	of high priority missions executed within the specified time.	Speed/Endurance/Payload
	Percent	of preplanned targets successfully attacked during operation.	Speed/Endurance/Payload

Table 1. MOE to MOP Mapping (NTA 1.2 to NTA 3.2).

Tasks	Measures of Effectiveness (MOE)		Measures of Performance (MOP)
	Units	Measures	
NTA 5.1 Acquire, Process, Communicate Information, and Maintain Status			
	Percent	of units are in communication with commander throughout planning and execution.	Payload
	Hours	to process status information and disseminate to subordinate units.	Payload
	Percent	of available information examined and considered in latest status report.	Payload
NTA 5.2.1.1 Review and Evaluate Situation			
	Hours	since last review of commander's plans.	N/A
	Percent	of information coming into the headquarters, of which the commander has cyclic management.	Payload
NTA 5.5.4 Conduct Electronic Warfare Support (ES)			
	Time	to rapidly reprogram warfighter sensors and seekers within the electromagnetic spectrum.	Payload
	Time	from receipt of data to classification to dissemination of tactical information.	Payload
	Number	of units with unresolved emitter ambiguities in the tactical picture.	Payload
NTA 6.1.1.3 Positively Identify Friendly Forces			
	Minutes	to confirm identity of unidentified target.	Payload
	Number/Percent	of forces accurately identified.	Payload
	Percent	of friendly casualties due to friendly actions.	Payload

Table 2. MOE to MOP Mapping (NTA 5.1 to NTA 6.1.1.3).

Tasks	Measures of Effectiveness (MOE)		Measures of Performance (MOP)
	Units	Measures	
NTA 6.3.1.5 Establish and Enforce Protection Perimeter			
	Y/N	Were unauthorized personnel, vessel, or vehicle permitted inside the minimum standoff zone?	Speed/Endurance/Payload
	Number	of minimum standoff zone penetrations.	Speed/Endurance/Payload
	Number	of minimum standoff zone penetrations successfully repelled.	Speed/Endurance/Payload

Table 3. MOE to MOP Mapping (NTA 6.3.1.5).

E. MULTI-CRITERIA DECISION-MAKING TOOL

1. Overview

Complex SoS like the UV sentry, consist of a multitude of interconnected systems and components. The tight coupling of these systems prevents the ability to optimize the overall system by optimizing each individual subsystem. This sets up a complex blend of system interrelationships of competing objectives. As systems become more complex, the ability to optimize capabilities becomes far more convoluted and difficult to improve using traditional methods. Multi-criteria decision-making methods and tools provide the means to optimize overall system performance by finding the optimal trade-off space between several competing system measures. MCDM theory and application could be a thesis topic by itself. However, in this thesis, MCDM is just another tool in the SE toolbox used for concept exploration, trade-off analysis, and system design.

2. Application

The keys to effective concept exploration is both ensuring the entire design space is exposed and having the ability to understand and communicate tradeoffs with stakeholders.

SAS JMP statistical analysis software was used as the MCDM tool to study the UV Sentry USV system design space. JMP software provides the means to utilize data

from the ship synthesis model to construct an effective and easy to use decision-making tool through DOE and RSM. JMP fuses powerful software analysis capabilities with dynamic data visualization providing the user with an interactive and flexible data management and display tool.

3. Design of Experiments (DOE)

DOE is a structured experimental approach to system or process analysis. The approach is used to quantify and examine multiple design parameter effects on an overall process or system design. The DOE is intended to "characterize" the system by determining which factors (variables) affect the response (outcome). System characterization is studied by conducting a screening experiment that uses fractional factorial designs. The screening experiment is intended to estimate the magnitude and direction of the factor effects (Montgomery 2001). After the screening test, the designer should be able to determine individual and combined (interactions) factor effects on the response variable.

DOE is used to find the minimum number of experiments that must be conducted to yield an accurate representation of the design space. This allows the designer to effectively and efficiently capture the critical process factors and their corresponding effects on the response while minimizing effort and required resources. DOE accounts for all possible factor dependencies from the start ensuring the response data covers all individual and interaction effects. This gives the designer full situational awareness and allows for the systematic removal of factors that do not affect the response.

4. Response Surface Methodology (RSM)

RSM is a collection of statistical and mathematical techniques useful in the development, improvement, and optimization of systems and processes (Myers and Montgomery 2002). This structured process uses second order curve fits of desired data to generate a minimum collection of designs based on groups of factors that permit the study of an entire design space. RSM uses a series of mathematically predefined orthogonal point designs to model the input-output relationship, which is then displayed visually to represent the design space for decision making (Katsoufis 2006). RSM allows

designers and stakeholders to effectively view the design space permitting concept exploration and tradeoff analysis. RSM is efficient, cost effective, and relatively simple compared to traditional methods.

There are a number of experimental designs used in RSM including the Central Composite and Box-Behnken methods. Each design presents a different experimental methodology and must be selected based on which best fits the system or process being studied. The Central Composite is used to develop the model due to its inclusion of the extreme factor points at the box vertices. Figure 15 shows a Central Composite design cube with three factors. This allows the designer to explore the entire design space including the extreme minimum and maximum factor areas.

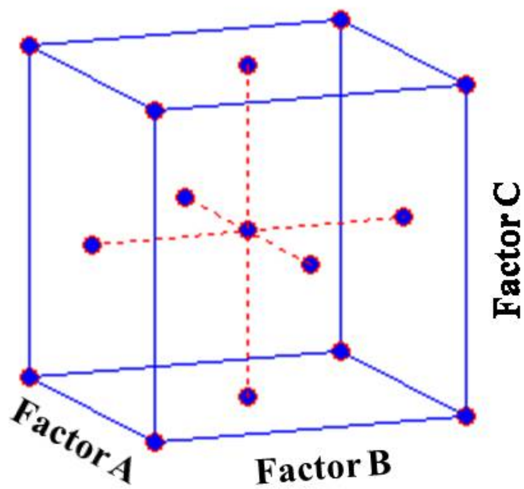

Figure 16. Central Composite Design Model.

The Central Composite design response surfaces require three levels for each factor to build the design space. Typically, threshold (minimum), midpoint, and goal (maximum) values are used as the three input factors levels. Determining an appropriate value range for each factor is vital to building a useful model. Designers should understand that these values determine the magnitude of the design space and must tailor their choices to build a precise model. A very narrow range may result in an exceedingly limited design space while a range that is too broad may result in a large fit error in the

regression equation, severely weakening the fidelity of the model. Designers must choose factors and parameters wisely and understand the consequences of their choices.

A second order RSM model is used to approximate the response once it is realized that the experiment is close to the optimum response region where a first order model is no longer adequate. The second order model is usually sufficient for the optimum region, as third order and higher effects are seldom important. Figure 17 shows the response surface second order regression equation for *k* (the total number) factors.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon$$

Figure 17. Response Surface Equation.

The b_0, b_{ii}, b_{ij} terms are constants determined from the multivariate regression, ε represents fit error, and the summations represent linear, quadratic, and interaction terms respectively. This equation represents the quadratic response surface for a given response y.

F. SUMMARY

Chapter III describes the elements and method for the proposed MBSE, architecture development, and decision-making process to aid in the transformation of capability needs to conceptual design for the UV Sentry USV. Chapter IV describes how to build the model and provides a brief case study to illustrate its usefulness and applications.

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IV. MODEL-BASED ANALYSIS

A. INTRODUCTION

The model-based analysis for the UV Sentry USV was conducted, as a part of the overall MBSE method, using SAS JMP statistical software. JMP provided the means to build an effective MCDM tool by fusing DOE and RSM techniques with predicted performance data from the ship synthesis model. This method gives UV Sentry stakeholders the ability to explore the USV conceptual design space, perform tradeoff analysis, and to make informed design decisions in the early stages of preliminary design, where changes are cost-effective and easy to implement.

B. CONSTRUCTING THE MODEL

Model construction began with the selection of the ship synthesis model. Choosing a suitable performance prediction model is critical to building an accurate MCDM tool. Model performance estimations are the factor and response inputs to the RSM equation and corresponding response surfaces. If these values are not accurate, the RSM driven MCDM tool will not yield useful information. A prismatic planning hull model was selected due to its relevance and use in current USV designs. There are countless ship synthesis models available and appropriate for use in this MBSE process. Model selection depends on many factors including customer capability needs, program constraints, technology readiness, and risk aversion. If the design strategy includes exploring the feasibility of different hull forms, designers may choose to select a number of ship synthesis models to analyze and compare. The type or number of models selected does not affect the MBSE process or the construction of the MCDM tool.

The next step involved building the design space. This process began by using the DOE feature in JMP to design the screening experiment. A three-factor Central Composite design was used to fully exploit the design space. Choosing the Central Composite design resulted in the fifteen tests shown in column two of Table 4. Vessel length, speed (velocity), and maximum duration (endurance) were selected due to their relevance in USV design. Payload capacity, displacement, fuel weight, and power were

chosen as the responses due to their importance in USV design. The ship synthesis model was exercised to study the feasible high and low limits in the model. This step was done to ensure the parameters selected for each factor were within the feasible design space. This process was necessary due to lack of data on specific prismatic planning hull point designs and the absence of specific capability needs and system constraints. The goal of this step was to determine actual values for the threshold, midpoint, and goal values of each factor that cover a potentially desired design space. The process yielded values of 32, 34, and 36 feet for vessel length and 24, 29, and 34 knots for ship speed. Three estimates for duration, 200, 400, and 600 NM, were chosen as the threshold, midpoint, and goal values respectively. Since maximum duration is an output in the ship synthesis model, the use of this variable as a factor required the use of values as close as possible to experimental design specification. The input values for payload (cargo) and fuel percentages were adjusted in an attempt to obtain duration values as close to the 200, 400, and 600 NM values as possible. The actual model outputs were then used as factor values for the table. The response values from the ship synthesis model were recorded in accordance with the DOE in the JMP matrix shown in Table 4.

	Pattern	Length	Speed	Duration	Payload Capacity	Displacement	Fuel Weight	Power
1	−++	32	34	540	0	18150	4819	873
2	a00	32	29	400	1928	18150	2891	592
3	−−+	32	24	610	1205	18150	3614	404
4	+++	36	34	210	2891	18150	1928	873
5	−+−	32	34	200	3614	18150	1205	404
6	0a0	34	24	390	3183	20987	2604	456
7	0A0	34	34	410	1736	20987	4051	971
8	000	34	29	400	2604	20987	3183	663
9	00A	34	29	610	868	20987	4919	663
10	+−+	36	24	220	4050	20987	1736	663
11	A00	36	29	620	0	23947	6878	1071
12	−−−	32	24	600	2407	23947	4471	509
13	++−	36	34	390	3439	23947	3439	737
14	00a	34	29	190	4815	23947	2063	1071
15	+−−	36	24	190	5502	23947	1376	509

Table 4. JMP Matrix.

JMP was used to process the DOE data to run the second-order, Central Composite RSM design model. JMP's "summary of fit" function was used to check the fitness of the RSM equation/model.

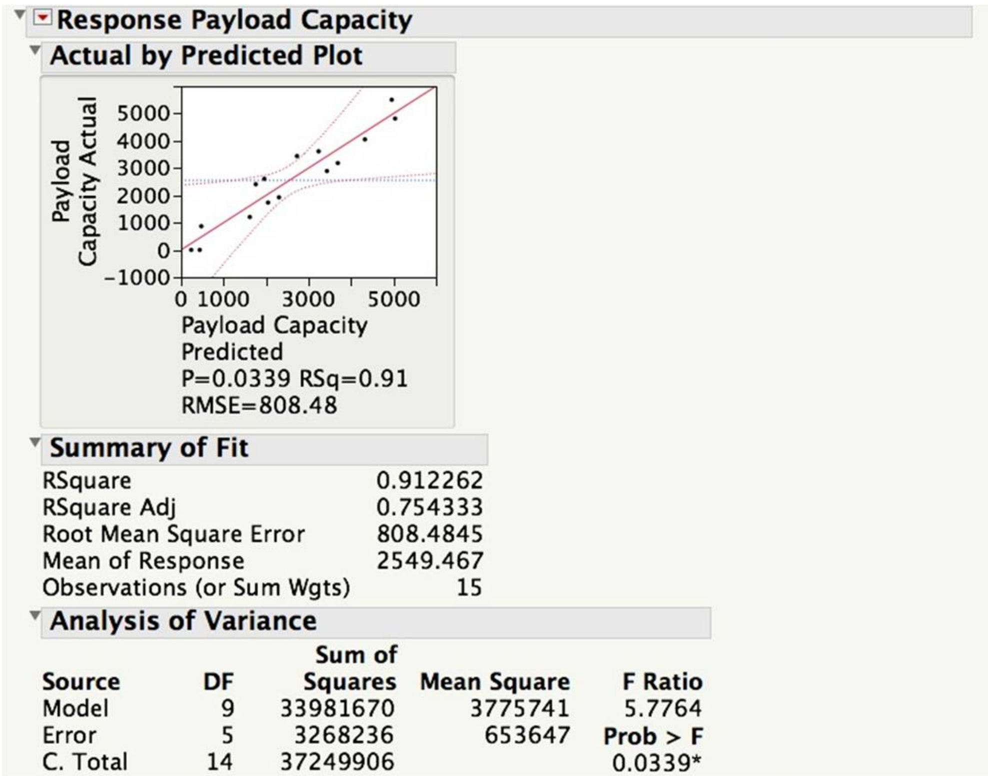

Figure 18. JMP Payload Capacity Statistical Summary of Fit.

Figure 18 displays the payload capacity statistical summary of fit in JMP. The payload response appears to be a reasonably good fit with a R^2 value of 0.91 and P-value of 0.03. The relatively tight grouping of points along the linear fit line confirms this assessment.

Once the equation is determined to have a reasonable statistical fit, the model is used to study factor interactions, analyze design space point designs, and communicate design trade-offs. The model allows the user to easily apply and manipulate an infinite number of variations into the design space. JMP's graphical interface enables the user to visualize design variants freeing the designer from the tremendous amount of work that traditionally goes into analyzing numerous potential point designs. The Profiler function,

presented in Figure 19, displays prediction traces for each factor. These "slices through the response surface" (SAS 2008) enable the user to change one variable at a time and see its effect on the predicted response. Evaluation of an individual factor's effect on the model can quickly and easily be performed helping a stakeholder decide the importance and relevance of the various factors.

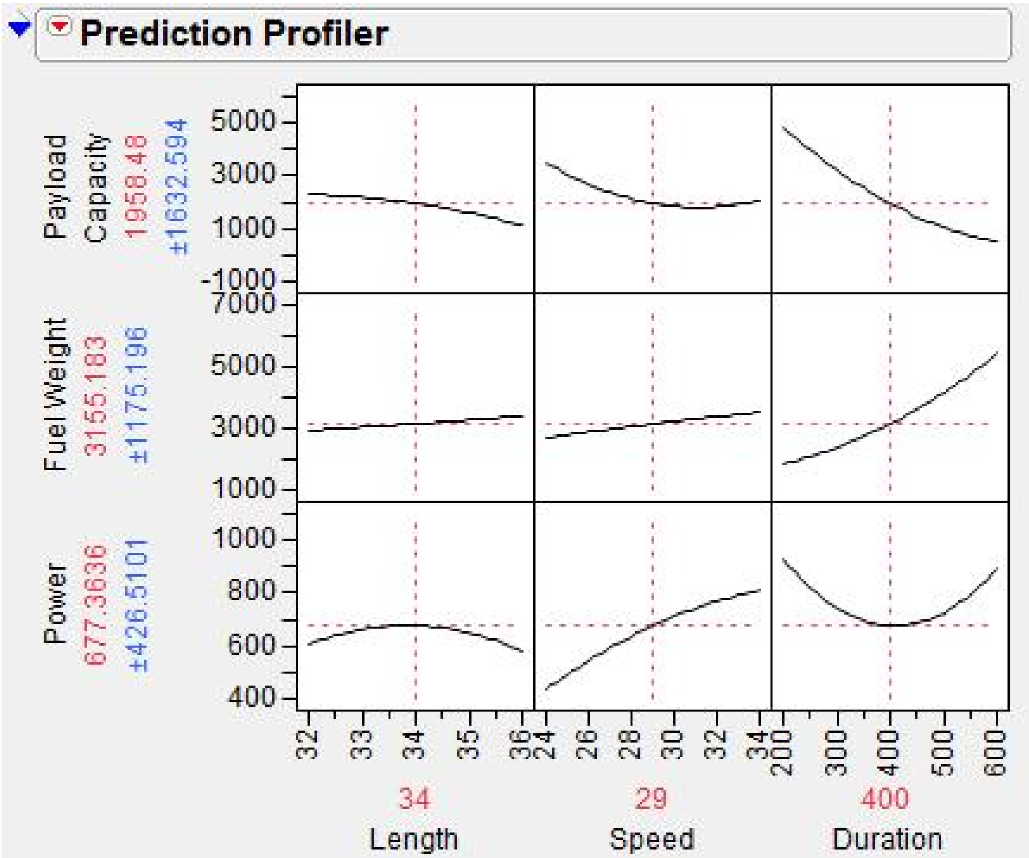

Figure 19. JMP Prediction Profiler.

The JMP graphical interface can be used to redefine the design space adding additional constraints and updating capabilities as stakeholders weigh in. Figure 20 illustrates the JMP Contour Profiler feature. This is an "interactive contour profiling facility useful when optimizing response surfaces graphically" (SAS 2008). The profiler uses a 2-dimensional cross section of the design space to illustrate how the responses vary with respect to the selected factors. In Figure 20, duration is selected for the y-axis and speed for the x-axis. The responses (payload capacity, fuel weight, and power) are

displayed as colored lines on the plot. The shaded regions represent infeasible design space regions with respect to the limiting constraints, leaving the white space as the feasible design region. In this case, the high limits of 2,500 pounds for payload capacity, 4,000 pounds for fuel weight, and 750 SHP for power were entered to illustrate the shading of the infeasible region. The crosshairs can be adjusted to show specific point values for various locations within the design space (under "Current X" in Figure 20). The contour profiler is a valuable tool to aid stakeholders in exploring and communicating potential designs within the design team.

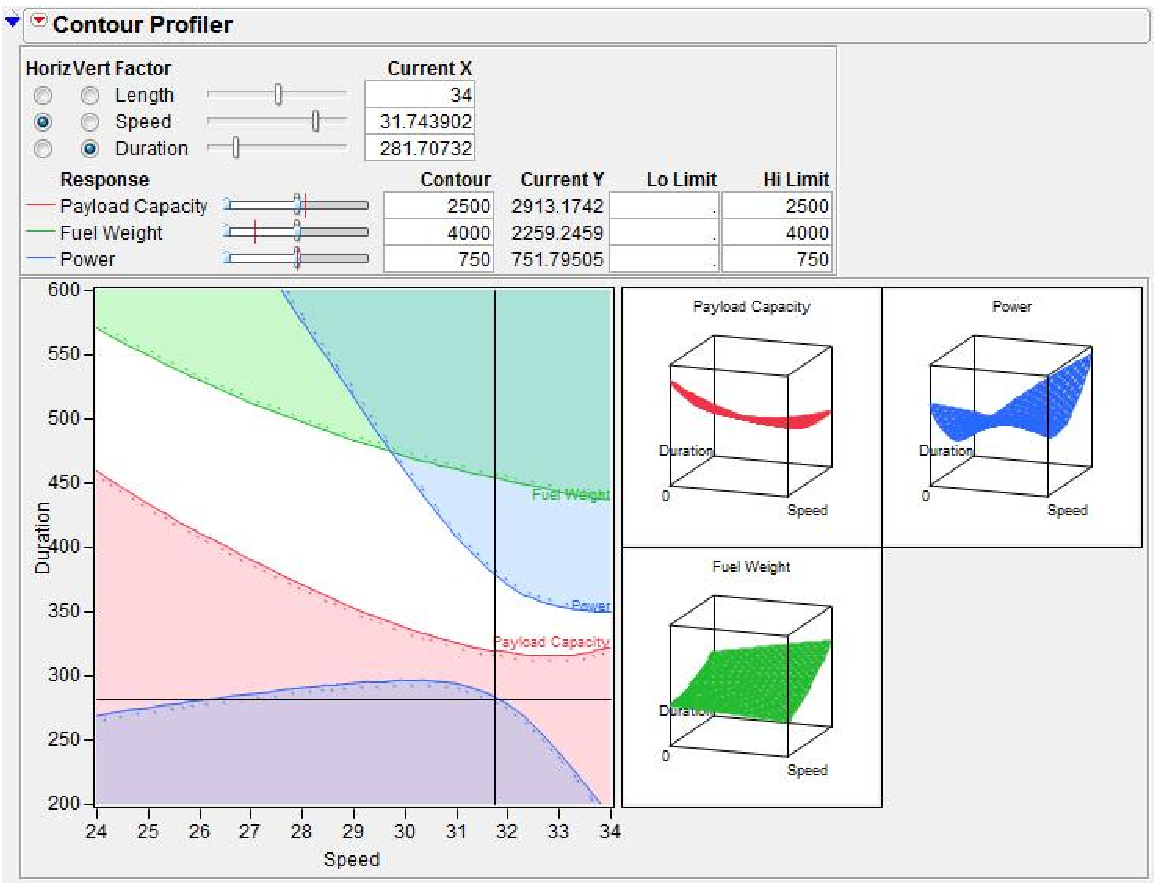

Figure 20. JMP Contour Profiler.

The mixture profiler, in Figure 21, shows “response contours of mixture experiment models on a ternary plot” (SAS 2008). This feature allows the user to display and analyze the 3-dimensional response surface when there are three or more factors in the experiment are components in a mixture.

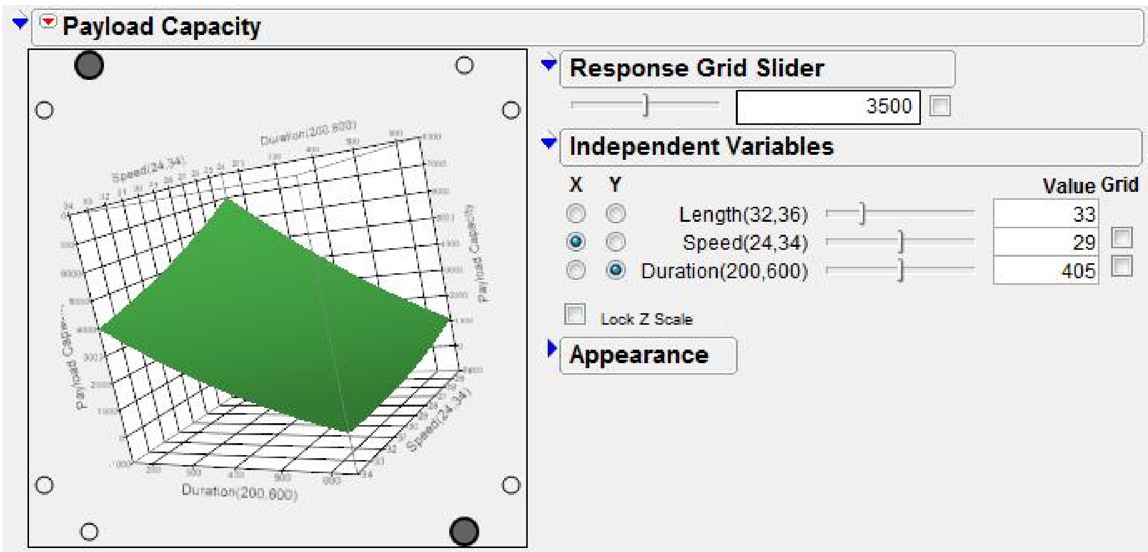

Figure 21. JMP Mixture Profiler.

C. CASE STUDY

1. Introduction

The following case study is a brief example of how the design model can be used to analyze a specific design concern regarding payload capacity. The example assumes the model is statistically fit and stakeholders are particularly concerned with the payload capacity of a proposed design for an 11-meter planing hull USV.

2. Example

Using the DRM and mission thread data from Chapter III, the USV design team built the initial system architecture and estimated the USV payload threshold to be 3,700 pounds. The team used the MCDM model to test this estimate’s impact on the team’s goal of meeting capability needs in a successful design. A contour plot was used to study

the impact of speed and duration on the payload estimate, Figure 22. The lines represent different payload values, in 200-pound increments, from 2,500 to 5,100 pounds. The shaded region represents the projected infeasible region below the 3,700-pound payload threshold. This illustrates where various combinations of speed and duration fall in the design space with respect to payload. The crosshairs show that a design with a 27-knot maximum speed and 320-NM maximum duration lies on the edge of the feasibility region. If, for example, the capability needs necessitate the USV to attain a speed of 30 knots with a 400-NM duration, the design team will suspect this point design to be infeasible requiring some form of action to take place. This step is useful but only considers deterministic values for speed and duration. The uncertainty involved with predicting the achievability of these values suggests that a probabilistic model is an improved way to investigate the design possibilities.

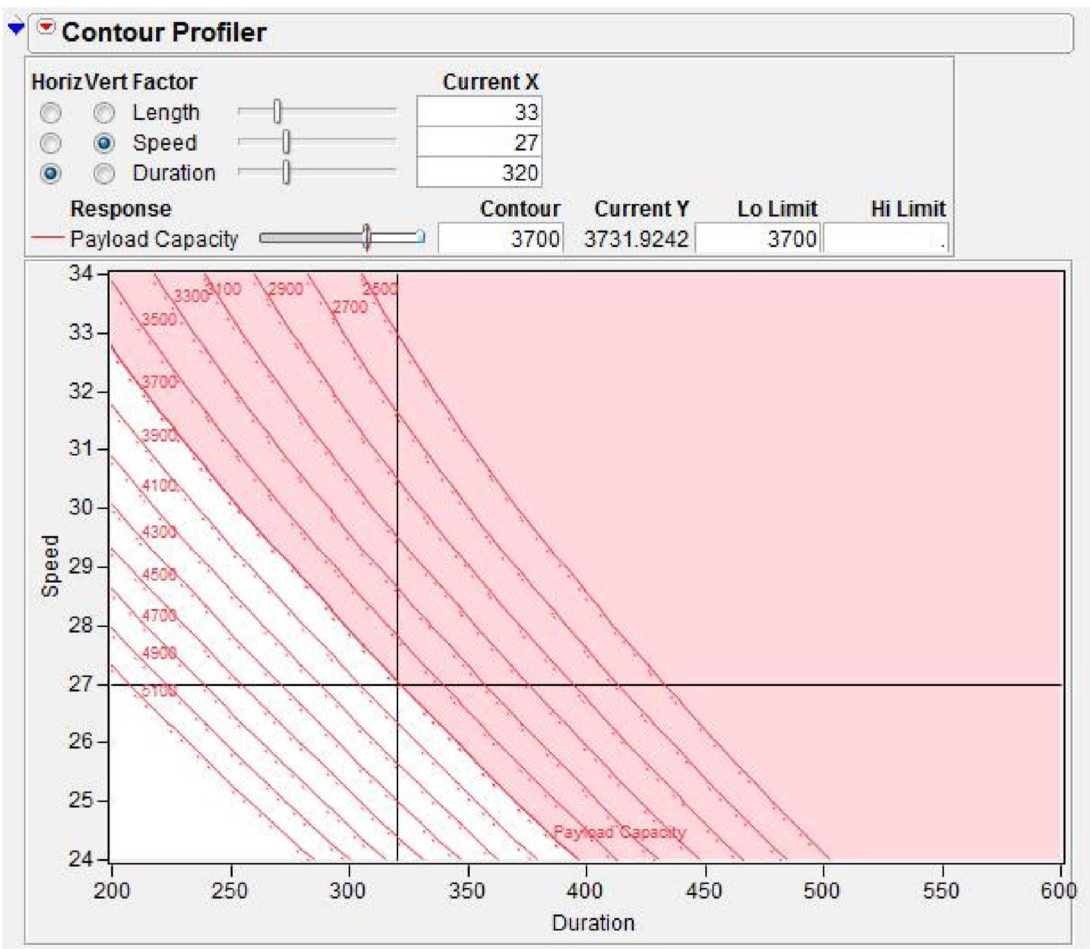

Figure 22. JMP Payload (case study) Contour Profiler.

Next, the design team uses the model to run a probabilistic simulation with random variable of speed and duration. The team uses triangular distributions for both variables with the lower, peak, and upper values shown in Figure 23. These values would be selected from subject matter expert estimations based on technology readiness, projected operational environment, and a number of "real-world" variations. Since the point design uses an 11-meter hull form, the length value is fixed at 33 feet.

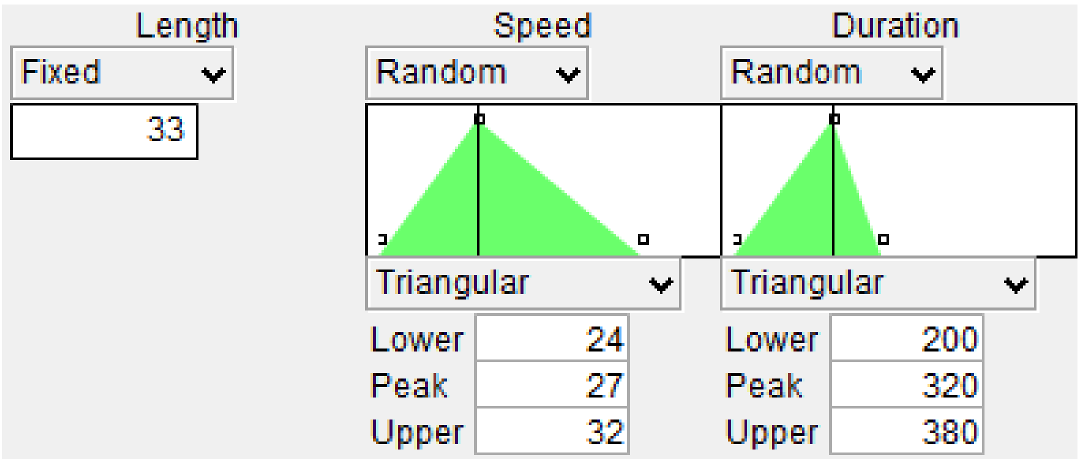

Figure 23. JMP Payload (case study) Simulation Probability Functions.

The team ran the trial simulation, using the JMP default of 5000 trials, to study the effect of length and speed variations on payload capacity. Figure 24 shows the JMP prediction profiler with the simulation results for payload capacity. The payload capacity distribution is displayed to the far right of the interaction curves with the simulation run mean and standard deviation listed below it. The simulation distribution and capability analysis are shown in Figure 25. The team included an upper and lower specification limit (USL/LSL) to represent their original maximum and minimum payload capacity values that were expected to meet predicted payload technology limits and system capability needs. Figure 25 shows the 5,000-pound USL and 3,000-pound LSL displayed on the distribution histogram (with box plot) and includes the specification limit "sigma" standard deviation data. The long-term sigma data is presented to show the chance that the outcome may fall outside desired specification limits, not to suggest anything about the process capability for this technology development study. This information provides the team with useful baseline data but will be much more valuable as the design evolves.

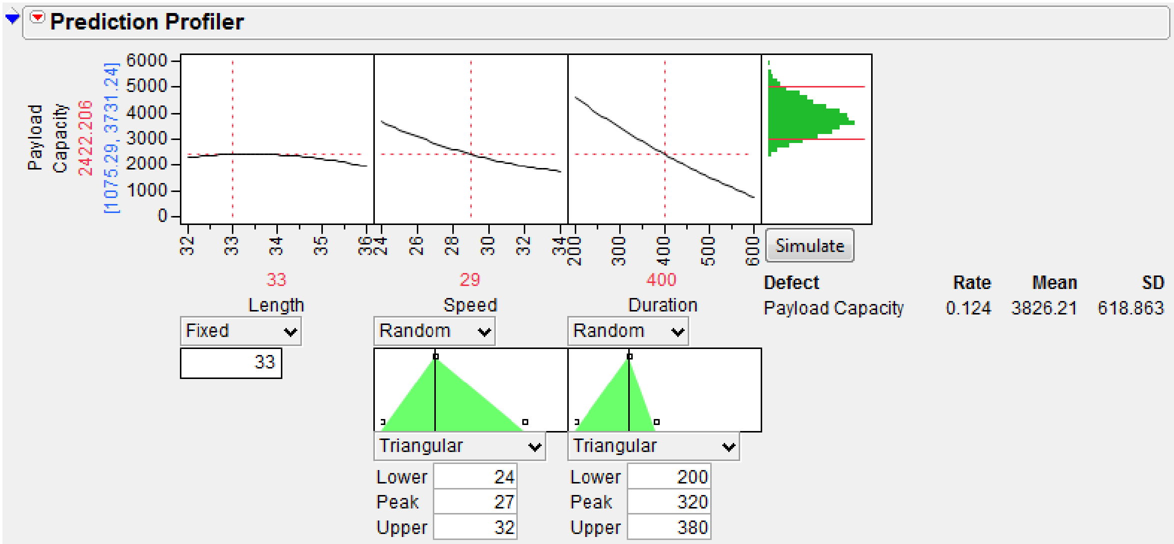

Figure 24. JMP Payload (case study) Simulation Prediction Profiler.

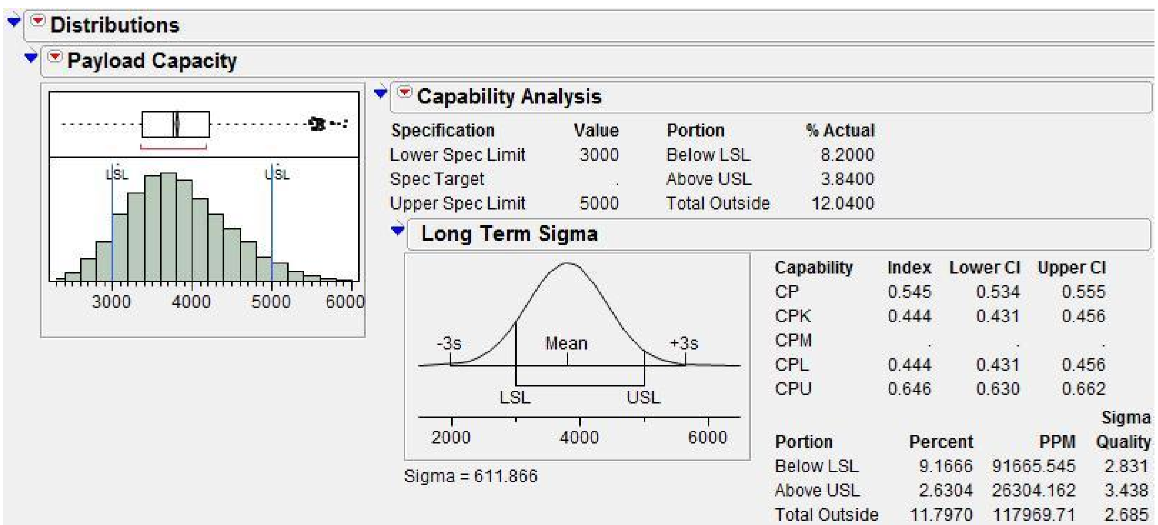

Figure 25. JMP Payload (case study) Simulation Distributions.

Finally, the design team uses the JMP simulation cumulative distribution function (CDF) plot to study the speed and duration variability impacts on payload capacity. Figure 26 shows the CDF for payload capacity from the outcome of the simulation run. This plot is used to show the probability of not achieving success per a given payload capacity, with respect to length, speed, and duration. Although the reverse CDF is more useful and easier to understand, JMP does not currently possess the capability to plot the

inverse of curve in Figure 26. Instead, to calculate the probability of achieving a given payload capacity, simply use the inverse of the probability read from the plot (i.e., subtract the value from 1). For example, by looking at the plot and using the inverse values, the team determines the probability of the USV achieving the desired speed and duration at the 3,000-pound LSL value is over 90% while the chance of accomplishing this at the 5,000-pound USL is less than 10%. As a further example, if investigation leads the design team to alter their payload weight estimate to 4,500 pounds. From the CDF plot they determine there is an approximately only a 15% chance that the desired speed and duration can be realized at this payload capacity with the current USV alternative. The team could then decide that the risk is too high for this alternative and would then explore corrective measures such as investigating lightweight payload component alternatives or interacting with stakeholders to see if lowering the maximum speed requirement, or operating multiple craft in tandem to lower endurance necessities would be acceptable in meeting mission requirements.

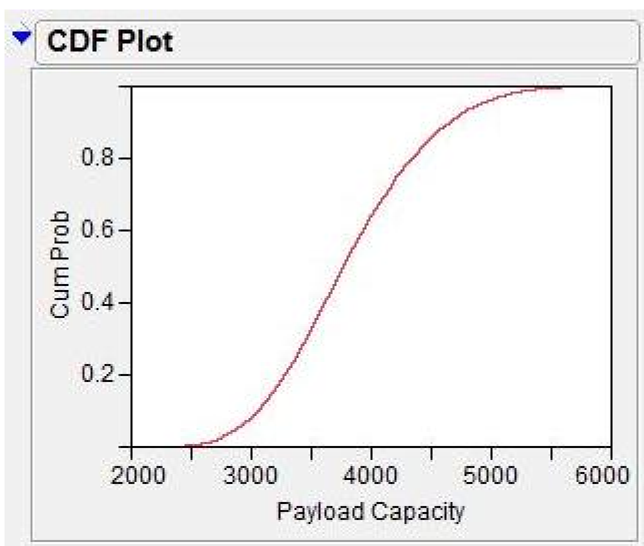

Figure 26. JMP Payload (case study) Simulation CDF Plot.

D. SUMMARY

The MCDM model described in this chapter is a highly effective analysis and communication tool for concept exploration and tradeoff study. The model is relatively easy to build and even easier to use. The program uses a commercial off the shelf

(COTS) software that is easy to find and install, and is compatible with most DoD computer systems. The most difficult step in constructing the MCDM tool is finding a valid performance prediction model. The model, or series of models, selected must provide an accurate representation of the physical behavior of the system or component being modeled. If the performance prediction model is inaccurate, the MCDM model will follow suit. In this case, a planing hull model was selected to predict USV performance. If a different hull form is selected, the design team must find a model that accurately predicts the performance of the type of hull being considered.

Input (factor) and output (response) variable selection is another critical step in the construction of the model. Variable selection is dependent upon their availability in the engineering synthesis models, the critical parameters of the system being designed, and the uncertainty of the relevant variables. In this case, length, speed, and duration were chosen to be the factors due to their relevance to the USV mission. The DRM set the baseline for the USV CONOPS and presented the system context and projected environment. From this, naval tasks were selected, from the NTTL, that formed mission threads required to meet system capability needs. These tasks were then mapped to applicable measures of effectiveness and to measures of performance (Tables 1-3). These measures of performance—speed, endurance, and payload—were all included in the model as either factors or responses. This method guarantees the warfighters' mission essential tasks and associated validation measures are addressed in the model and in the design.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The methods described in this thesis are relatively straightforward but highly effective when integrated. The tools and techniques employed to build the MCDM model are not unique to this thesis. The original concept proposed herein involves the unique amalgamation of these established tools and techniques to construct an effective and practical MCDM model. The first three chapters describe the necessary background and contextual data to set an appropriate knowledge base for the rest of the work. The fundamental design concepts, scope and methodology, design tools and techniques, and UV Sentry/USV background data are described. Chapter IV tied the concepts together by describing how to build the model and stepping through an example of its usage. In addition, the model was used to study the impact of stochastic inputs and uncertainty in a design example. Chapter V provides conclusions for this work and recommendations for future study.

B. CONCLUSIONS

The MCDM model and techniques described herein provide the UV Sentry team with a highly effective conceptual design tool for developing an USV. The thesis offers an alternative approach to traditional conceptual design based on a capabilities-driven, model-based, SoS engineering process including explicit consideration of variable uncertainty. This holistic approach to system design keeps the design concepts and the designer in the feasible region with respect to physical, systematic, and capability constraints. The methodology is effective and the thesis presents a tool set to enable design, development, and assessment of alternative system concept architectures for an autonomous USV in a SoS context. The MCDM model enables designers to perform a solution neutral investigation of possible alternative physical architecture concepts. This ensures a consistent quantitative evaluation of warfighting capability, suitability, effectiveness, technology maturation, and risk before and during a program execution.

This effort is in support of an extended program to design a system of unmanned systems intended to provide the DoD with a coordinated, multi-domain, multi-mission, autonomous security and warfighting asset.

The tools and techniques presented in this thesis are only as good as the system designer that uses them. System stakeholders are still responsible for following good engineering and architecture development practices including proper problem definition and effective analysis of alternatives. System stakeholders must also promote adept communication and thorough tradeoff exploration in design development. This includes true, unbiased exploration of alternative system architectures capable of meeting capability needs. Preconceived notions of engineering solutions may limit the design space resulting in a sub-optimal system design.

This MCDM method described is not limited to UV Sentry, USVs, or SoS. The concepts and tools are flexible and universal. The MCDM model is relatively easy to build, manipulate, understand, and change. It can be effectively utilized to aid stakeholders in making conceptual design decisions in the development process of any system, component, or SoS.

C. RECOMMENDATIONS

This work is a solid first step in the quest for ultimately developing a UV Sentry SoS. Some additional study would advance the ability to perform more extensive MBSE analysis and design. Recommended areas for follow-on study include:

- Using an operational simulation of the warfighting capability to link the front end of an executable architecture model, connecting from the warfighting simulation used to measure the achievement of MOE, traced through the operational activity, operational task, function, requirement, and component elements to the UxV design spaces. This would provide quantitative input to stakeholders from an operational viewpoint.

- Modeling the requirements specification limits in the responses to investigate robustness of MOE to MOP. This would provide the bounds to

achieve a quantitative technology risk assessment based on the uncertainty in the technology development and its impact on the achievement of the warfighter's needs.

- Including cost-effectiveness-risk trade-off along with the technology impact assessment on the USV. The system evaluation should include technology assessments with direct interface with UV Sentry technology areas, suitability evaluation, effectiveness evaluation, cost analysis, and risk analysis. This would provide a holistic trade off assessment for all stakeholders to use for consistent decision making.

- Extending the USV methodology to allow assessment of cross platform interactions across all UxV in order to perform SoS level trade-offs. The overall goal of UV Sentry is to define the optimal combinations of UxV to meet stakeholder operational needs, from mission capabilities and operational activities. The allocation of functions must be allowed across the UxV platforms to determine alternative solutions in a SoS sense, and not by presuming specific platform configurations of physical components.

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